Micromegas X-ray detectors for (Baby) IAXO

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Valencia - Spain

Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

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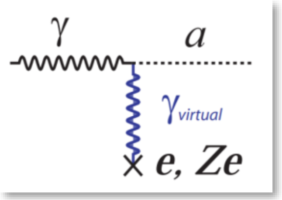
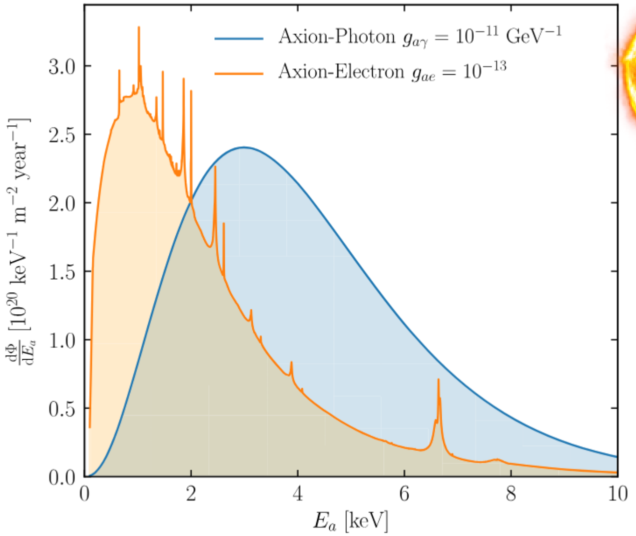
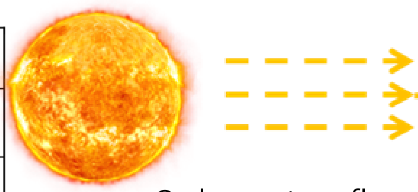
- Solar axions and helioscopes
- Helioscope generations: BabyIAXO and IAXO
- Micromegas prototypes
- Background studies

Solar axions and helioscopes

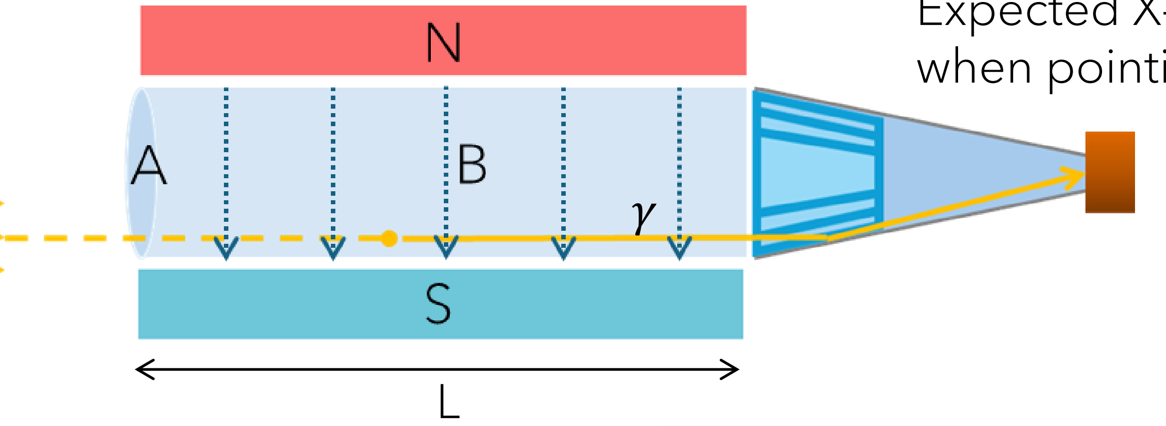
Production: stars produce axions from thermal photons via Primakoff effect







Solar axion flux



Expected X-ray signal when pointing to the Sun

Detection: conversion of axions into photons in the presence of a magnetic field

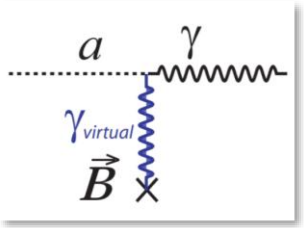


Figure of Merit (FOM)

	magnet		detectors		optics		exposure
$g_{a\gamma}^4 \sim$	B^2L^2A	$\times$	$\varepsilon_d b^{-1/2}$	$\times$	$\varepsilon_0 \alpha^{-1/2}$	$\times$	$\varepsilon_t^{-1/2} t^{-1/2}$

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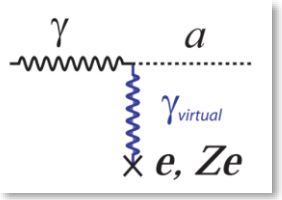

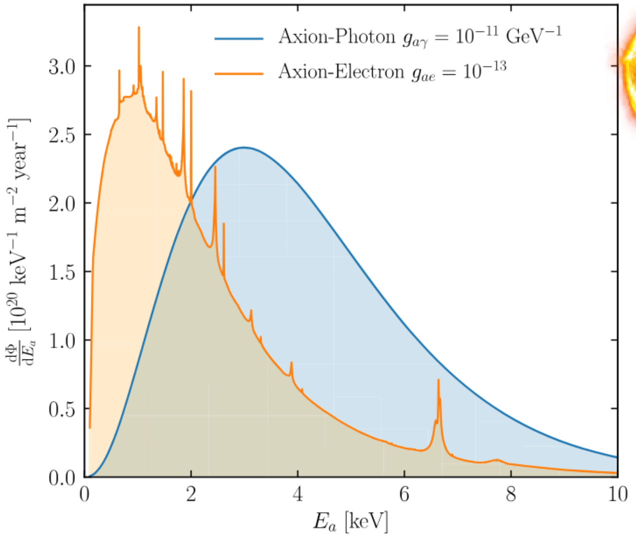

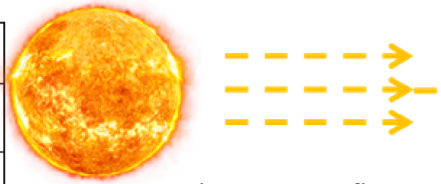

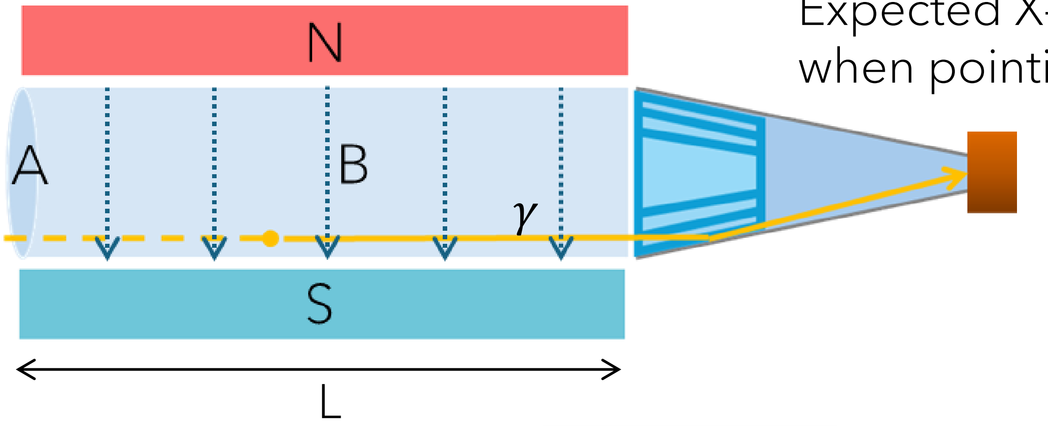

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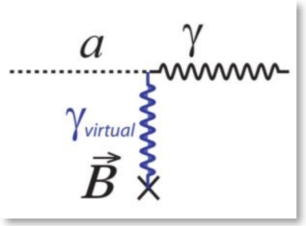

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Helioscope generations

CAST

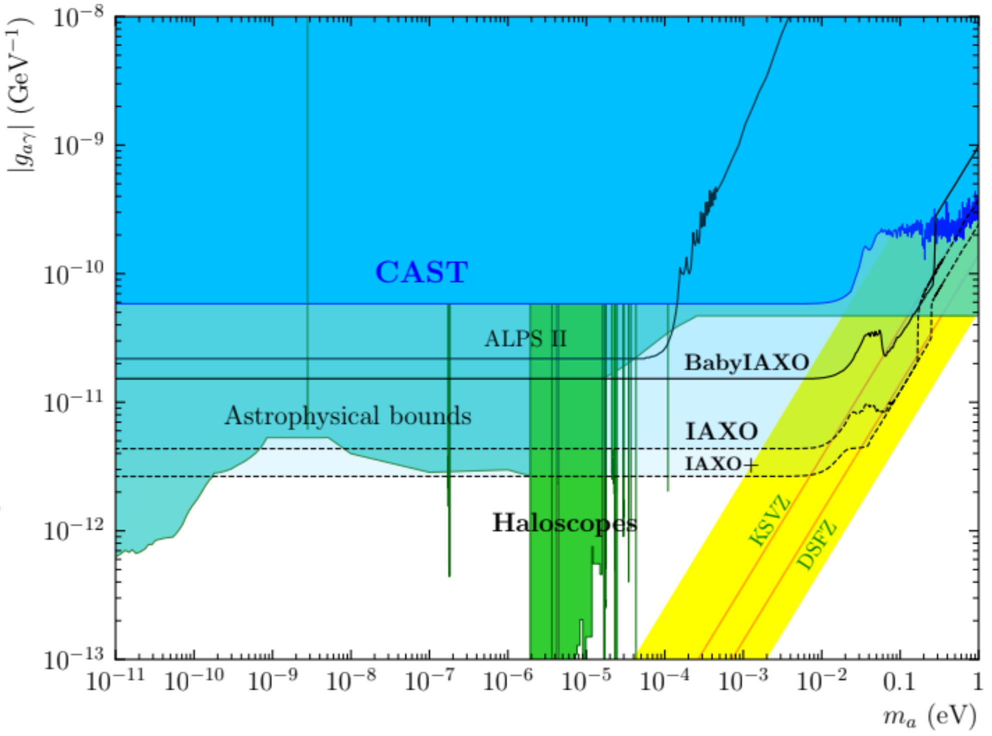
- The most sensitive helioscope so far
- Has reached similar level to HB stars bounds

BabyIAXO

- Sensitive to realistic QCD axion models
- Improves signal-to-noise ratio (SNR) by a factor 10^2
- Background requirement ~10^{-7} c/keV/cm^2/s

IAXO

- Improves CAST SNR by a factor 10^4
- Improves CAST sensitivity to $g_{a\gamma}$ in more than a factor 10
- Background requirement ~ 10^{-8} c/keV/cm^2/s



Phys. Rev. Lett 133.22 (2024): 221005.

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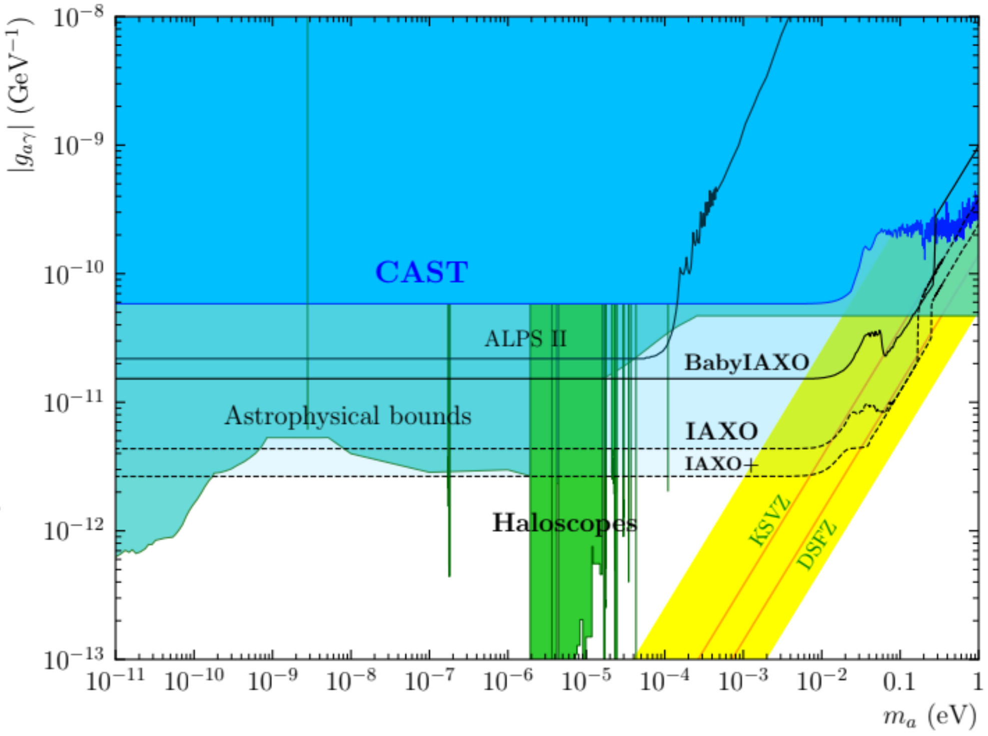

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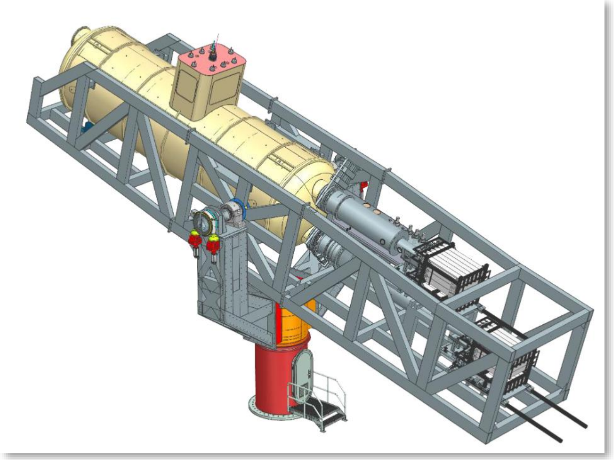

10.1007/JHEP05(2021)137

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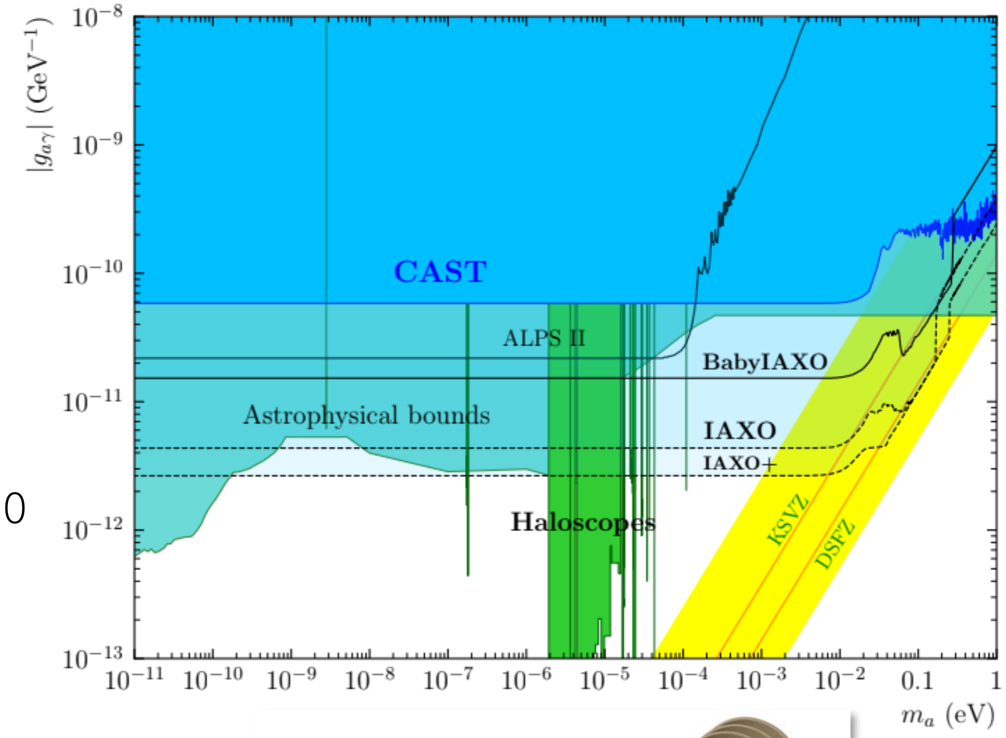

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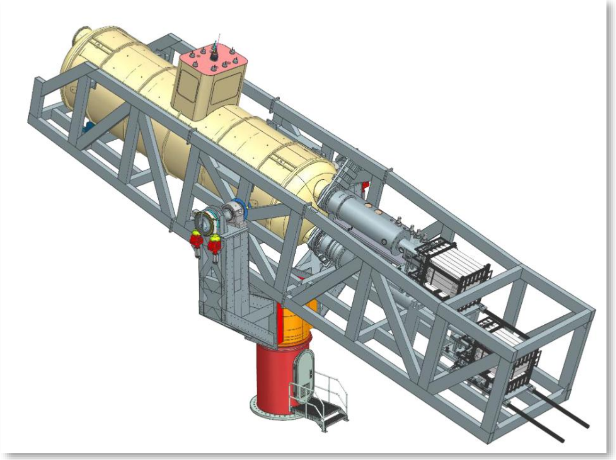

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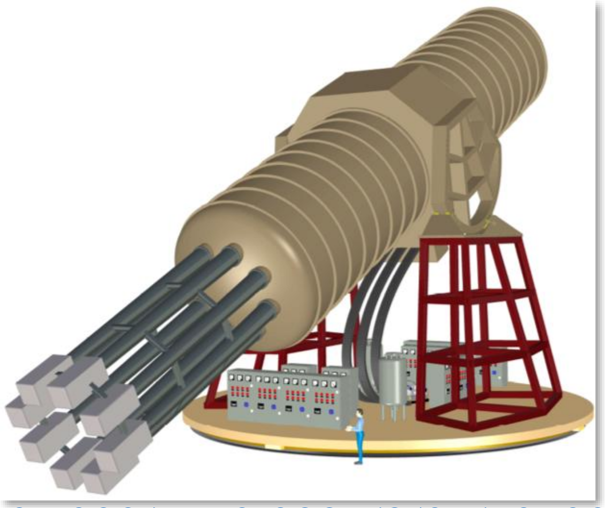

10.1088/1748-0221/9/05/T05002

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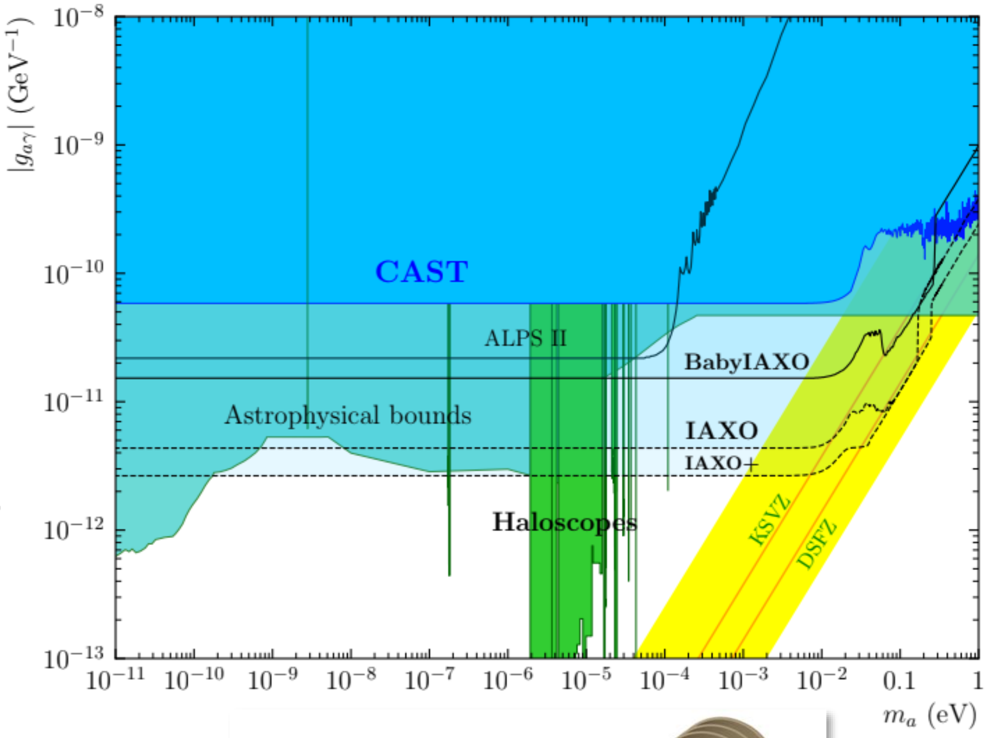

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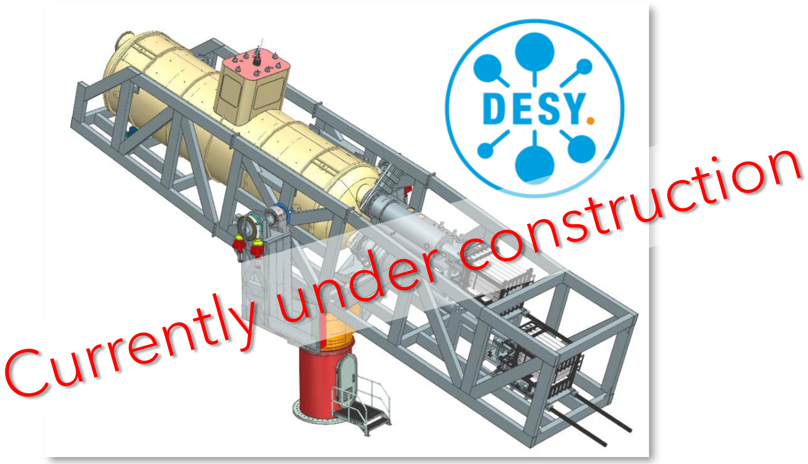

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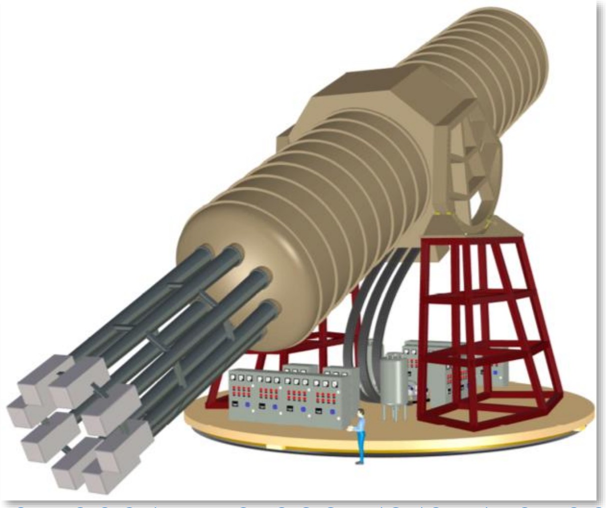

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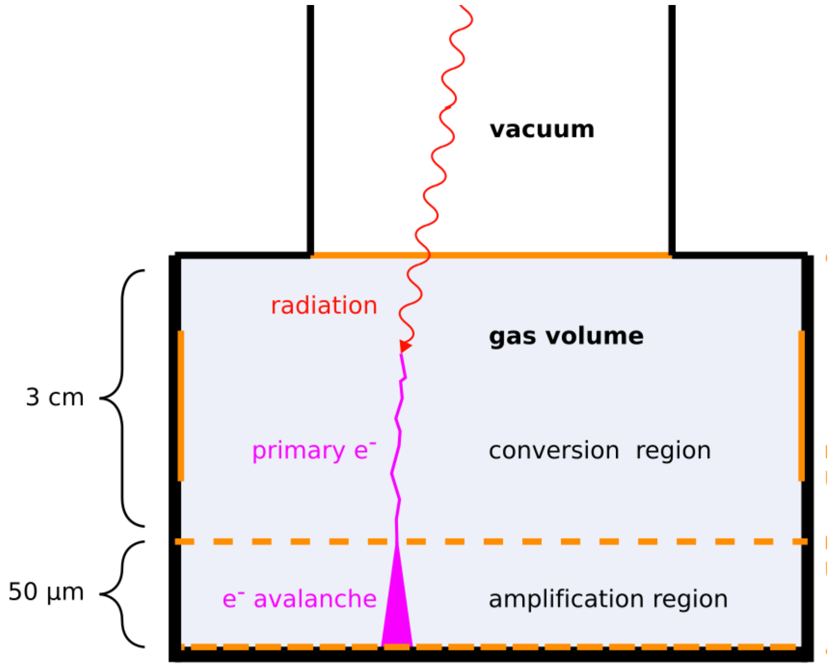
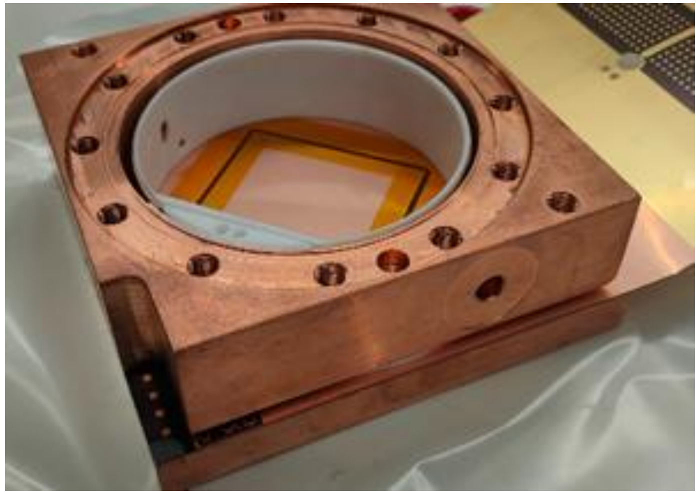
BabyIAXO baseline technology

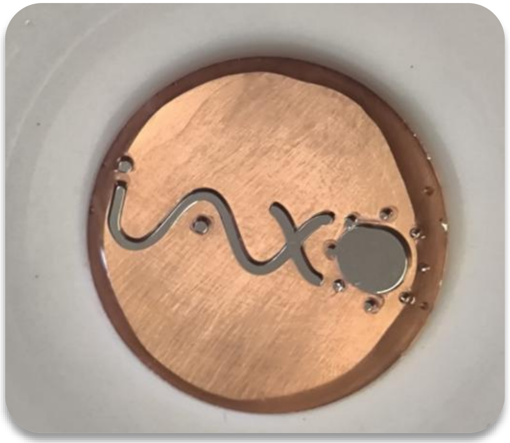


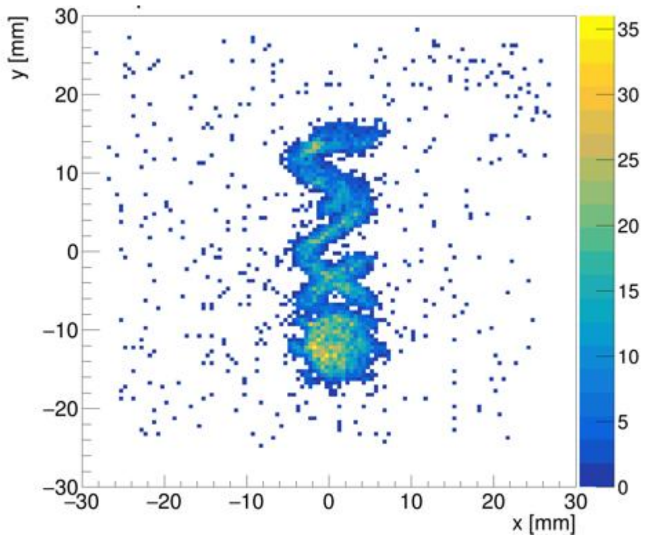


Current baseline technology is Micromegas but there are other technologies under study (GridPix, MMC, SDD, TES)

- 3 cm drift distance Gaseous Time Projection Chamber
- Microbulk Micromegas readout
  - 50 µm amplification gap
  - 120 x 120 strips (6 x 6 cm^2)

✓ Very homogeneous amplification gap, uniform gain
✓ Microbulk: intrinsically radiopure
✓ Good energy and spatial resolution
✓ Pixelized readout gives topological information

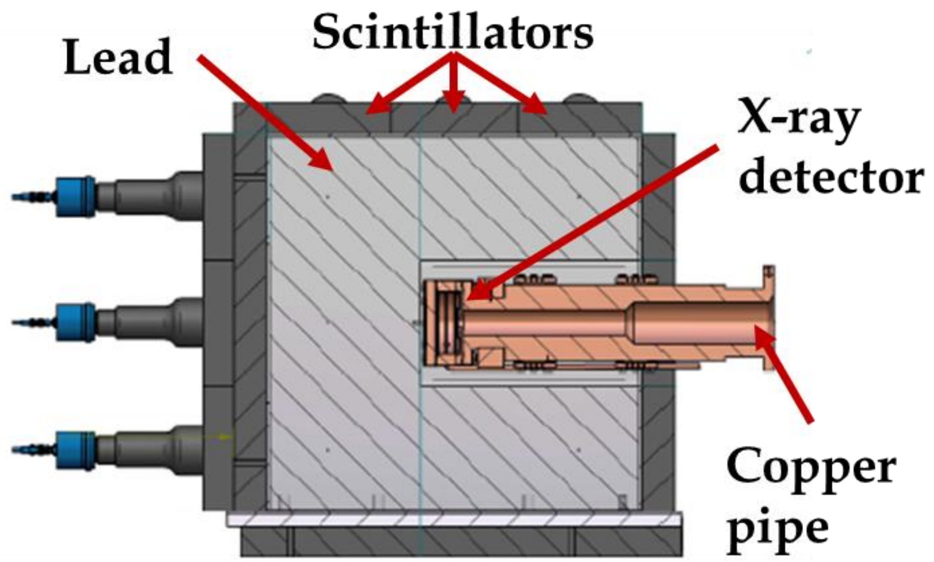




BabyIAXO background requirements: 10^{-7} c/keV/cm^2/s in the ROI (1-10) keV

IAXO-D1: state of the art on ultra-low background techniques

- Radiopurity
- Shielding
  - Passive: 20 cm of lead
  - Radiopure copper: 2.5 cm
  - Active veto system (plastic scintillators) for cosmic rays and secondaries
- Event discrimination strategies
  - Micromegas: event topology (x-ray events)
  - Veto system: multiplicity



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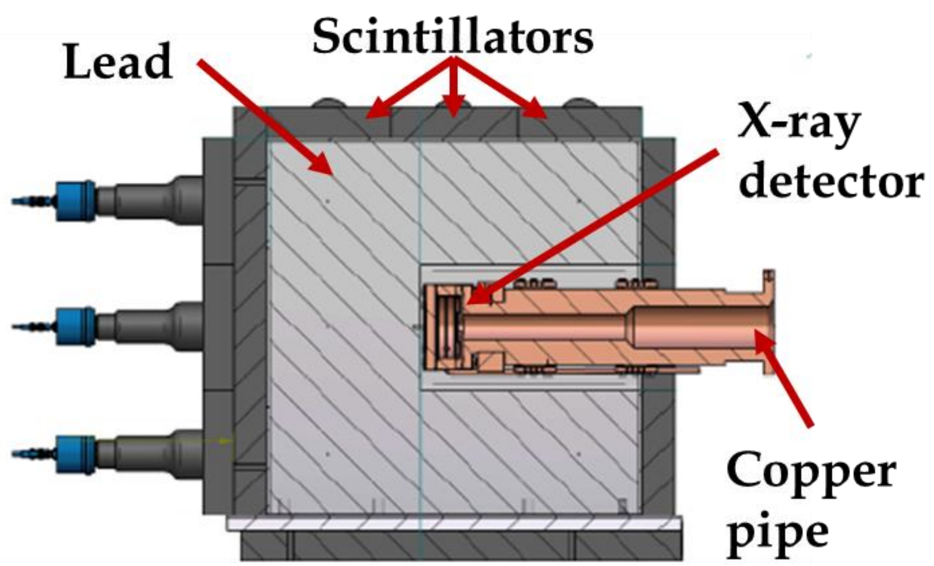


Background measurements + Simulations

Different prototypes to optimize background and event discrimination strategies

Background model in progress
Geant4 simulations + realistic event reconstruction with REST-for-Physics

BabyIAXO Micromegas detectors

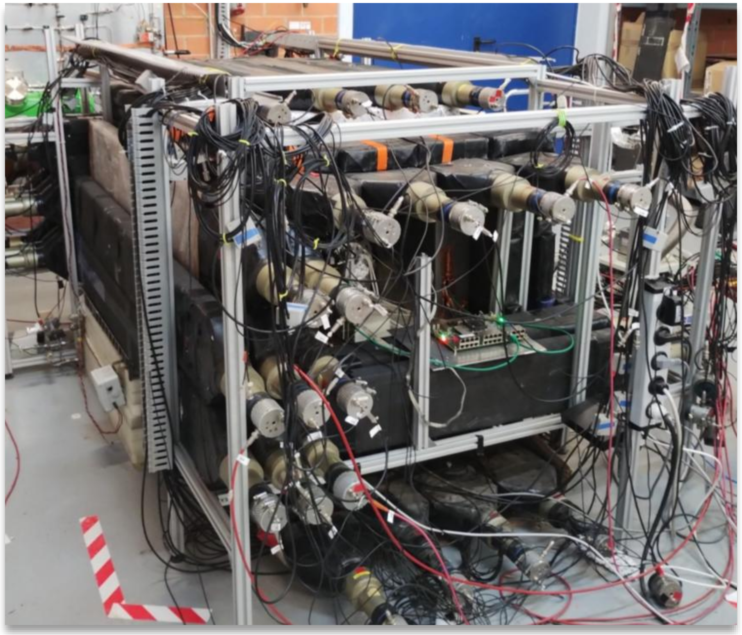
Surface level

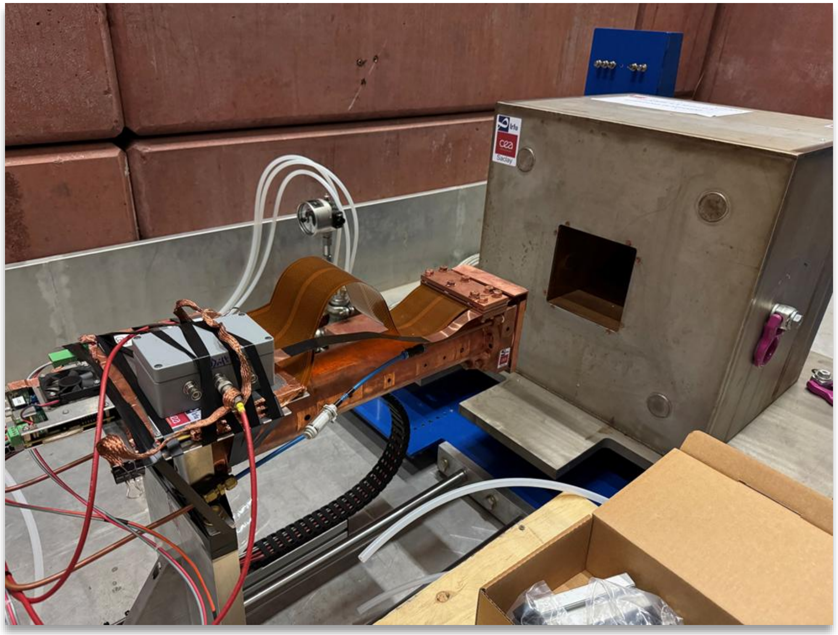
Underground

Laboratorio Subterráneo de Canfranc
Cosmic muon flux reduced by a factor 10^4

Zaragoza

CEA-Saclay → Now in DESY!





- Effect of multi-layer veto system to tag cosmogenic neutrons (in addition to muons)
- Measure background on experimental site
- Intrinsic detector background
- Test of different gas mixtures

Goals

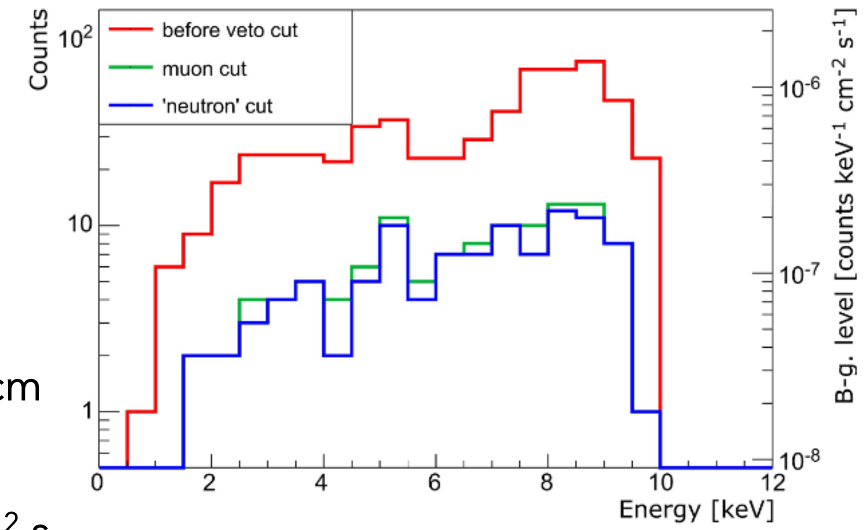
- Study of the effect of multi-layer veto system to tag cosmogenic neutrons (in addition to muons)
- Optimization of background discrimination techniques

→ Experience from previous prototype (IAXO-D0)

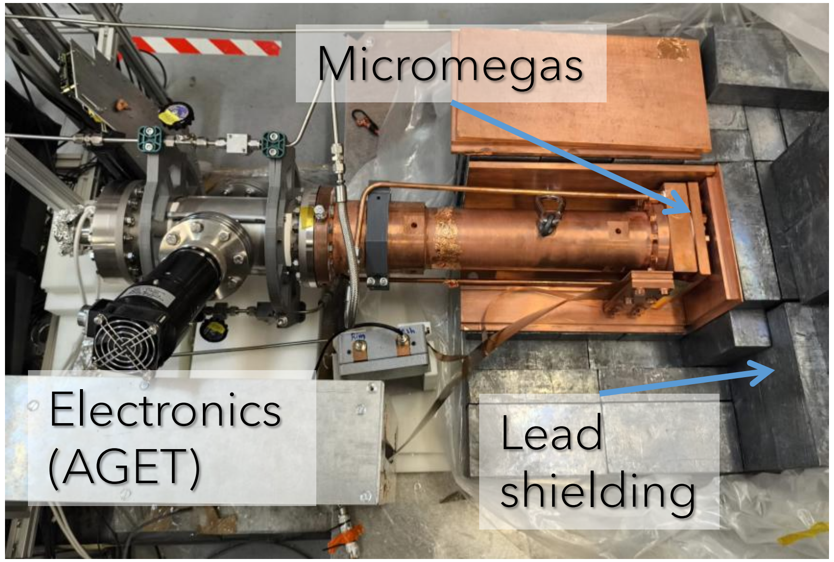
- CAST microbulk MM
- 48.5%Xe-48.5%Ne-2.3%Iso
- Neutron cut: high multiplicity in veto system

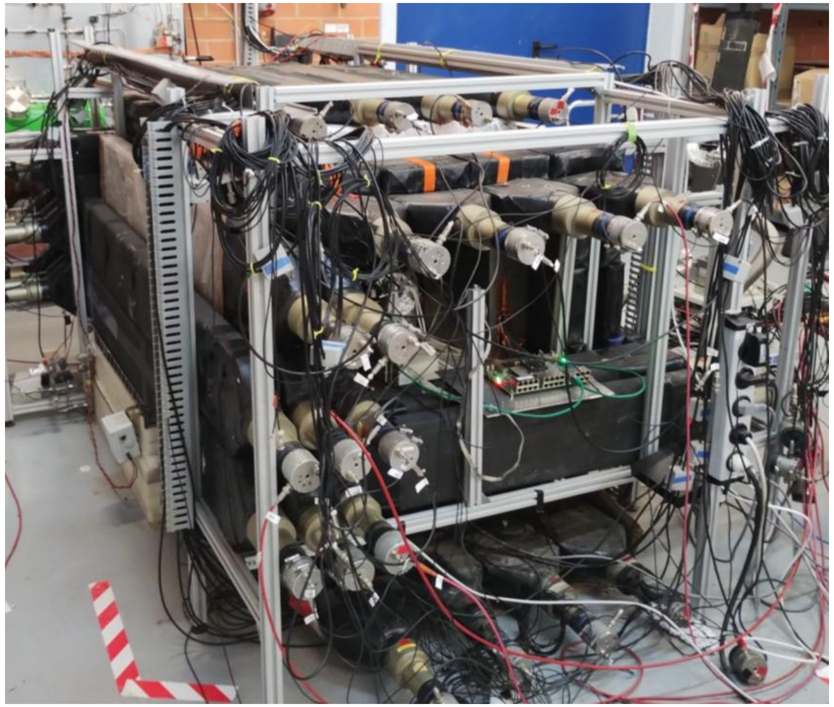
Background in [2-7] keV, r < 1 cm after 51 days:

$(8.6 \pm 1.2) \times 10^{-7}$ counts/keV·cm²·s



Frontiers in Physics 12 (2024): 1384415.





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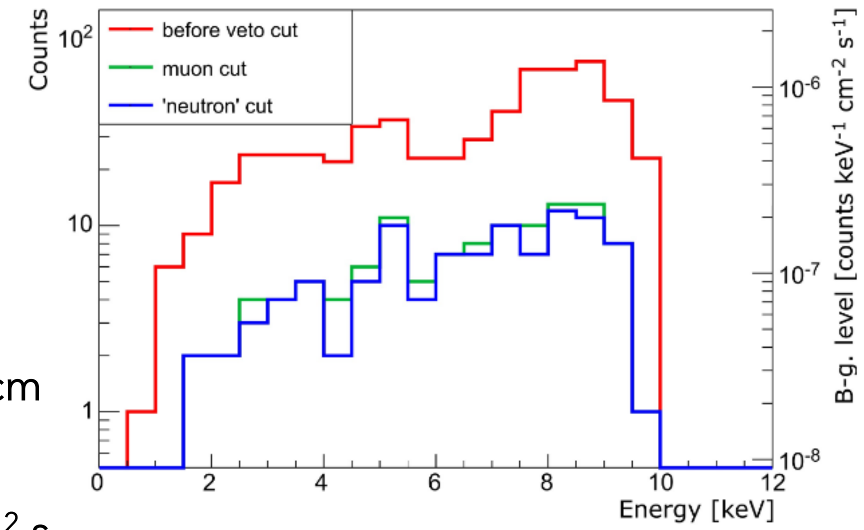

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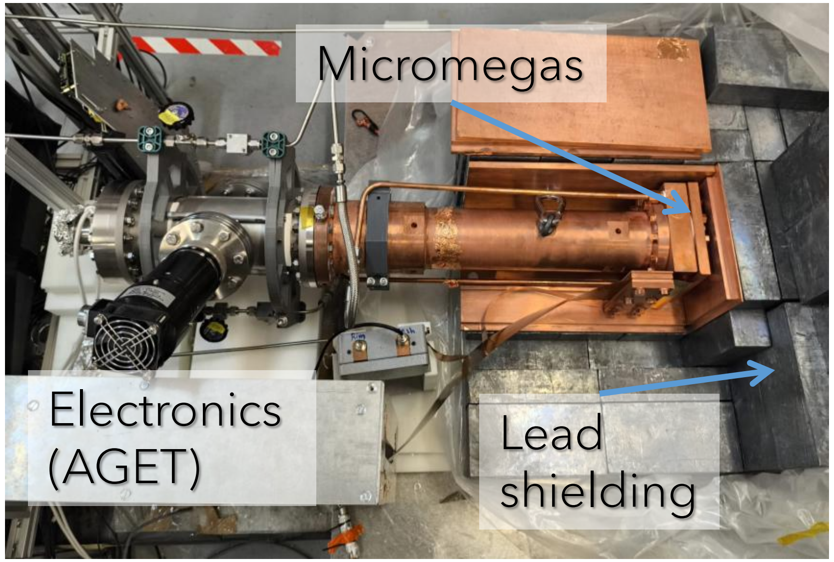
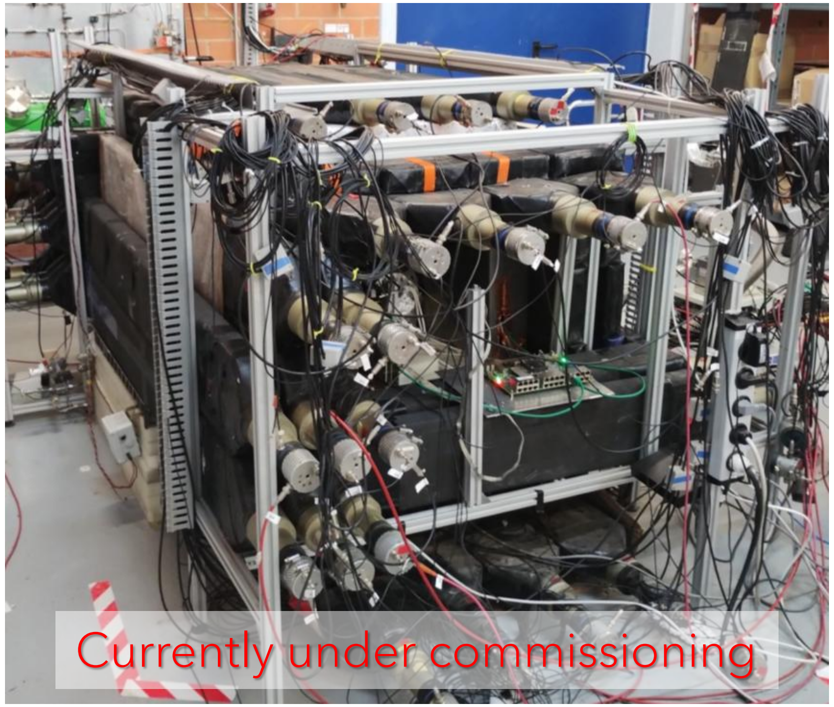
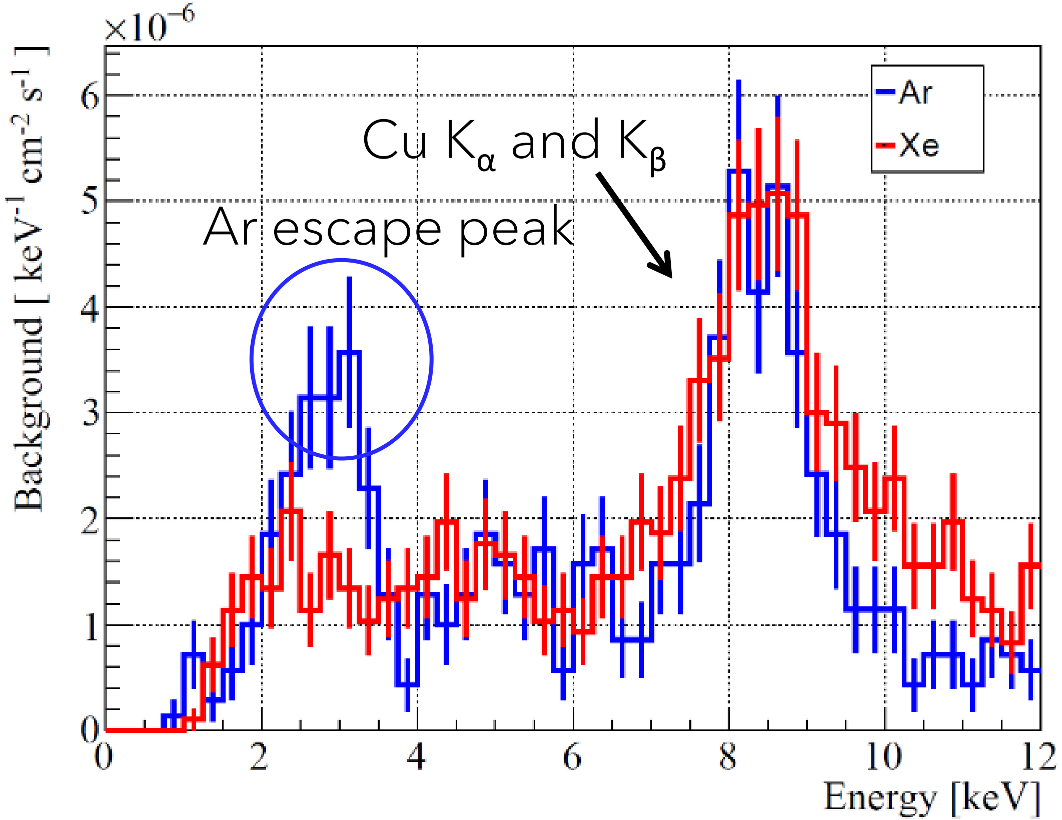




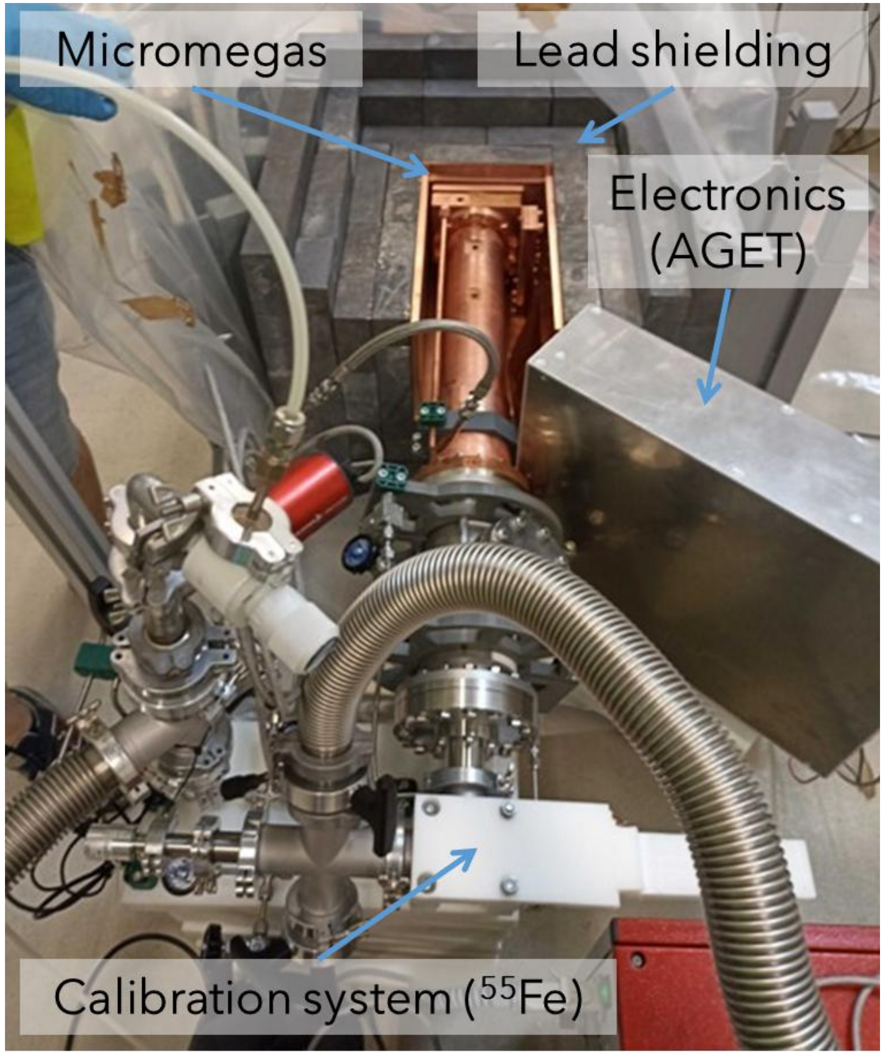
Goals

- Study of intrinsic background
- Optimization of the performance with different gas mixtures: **Ar+Isobutane and Xe+Ne+Isobutane**



Phys. Rev. Lett 133.22 (2024): 221005.

Set-up



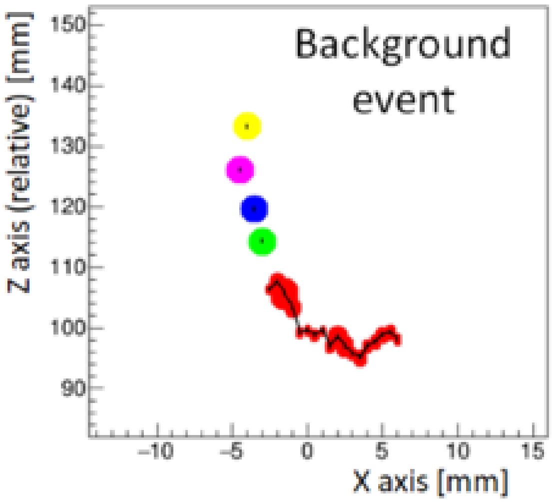
Nominal gain

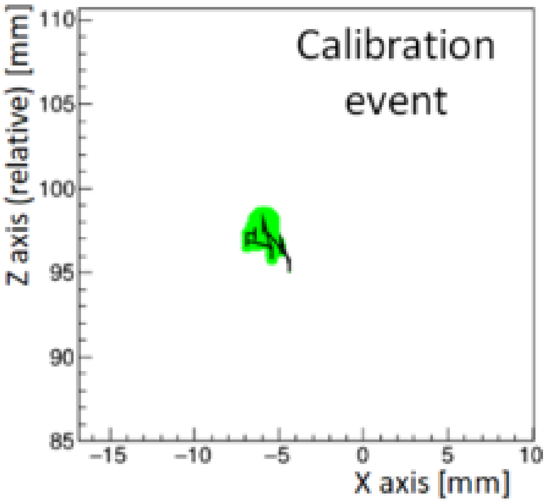
Data taking conditions

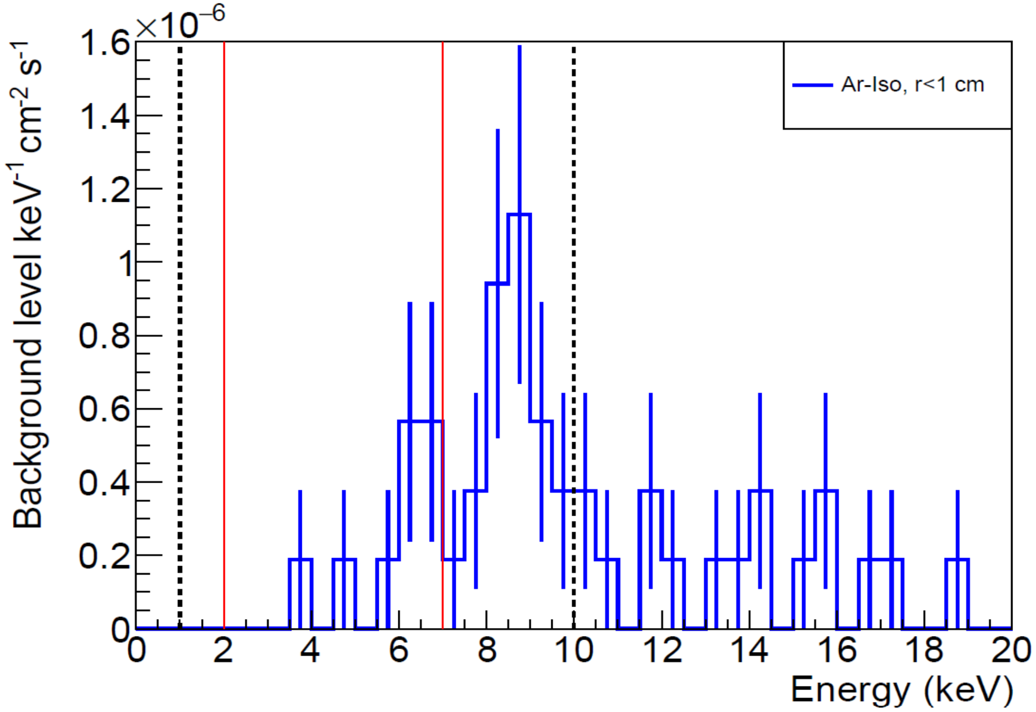
- 99%Ar + 1%Isobutane (premixed)
- No recirculation
- HV_{mesh} = 325V
- $HV_{cathode}$ = 750V
- P = 1.25 bar
- Gas flow 2l/h

Analysis

- Background rejection algorithm based on event topology
- 80% software efficiency
- Energy cut: [2,7] keV
- Fidutial cut: r < 1cm
- 9 events after 39.15 days of data taking







Background level: $(1.7 \pm 0.6) \times 10^{-7}$ counts/keV·cm²·s

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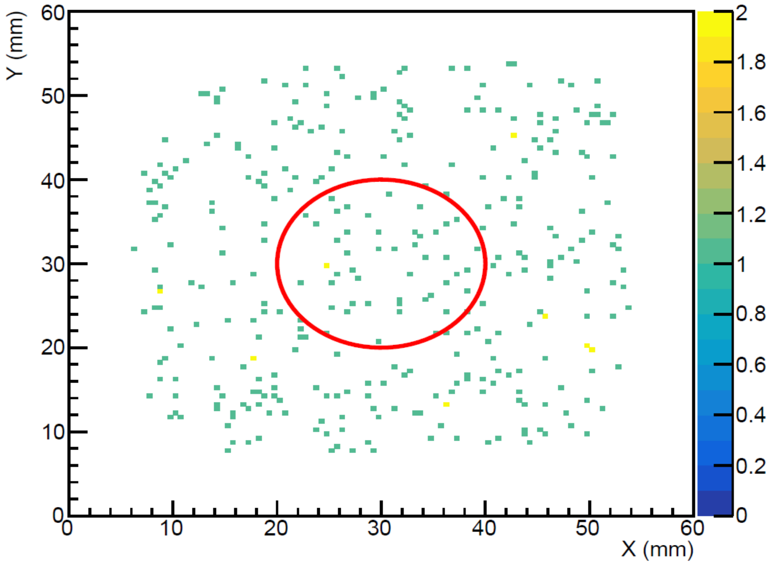
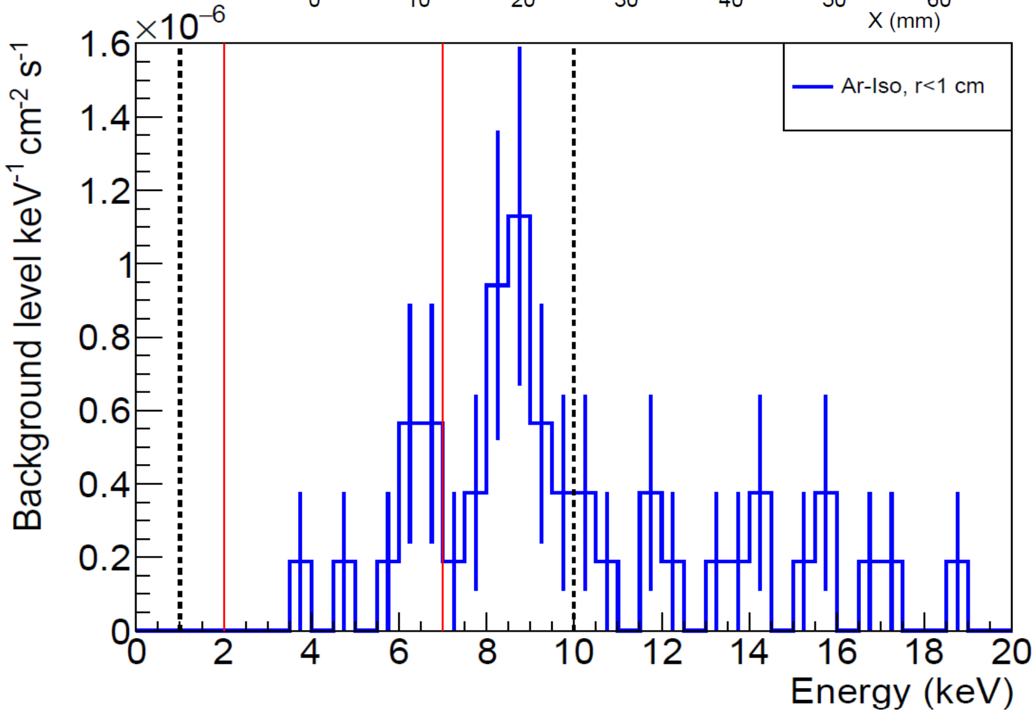




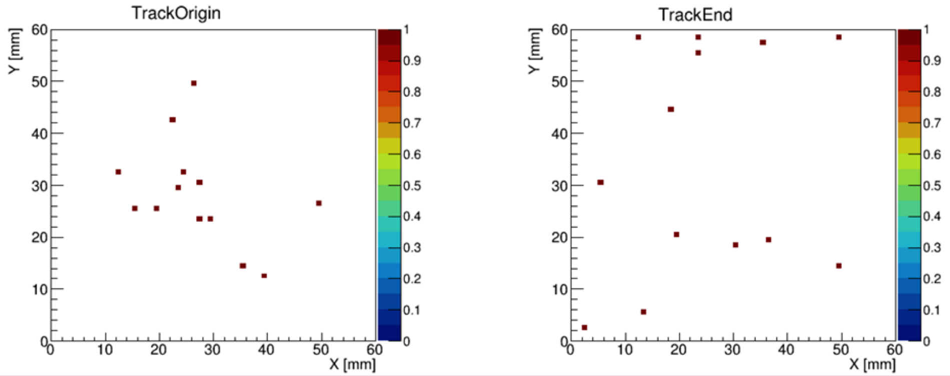
Low gain (alphas)

Data taking conditions

- Premixed gas cylinder of 99%Ar + 1%Isobutane
- No recirculation
- HV_{mesh} = 235V
- $HV_{cathode}$ = 750V
- P = 1.4 bar
- Gas flow 2l/h

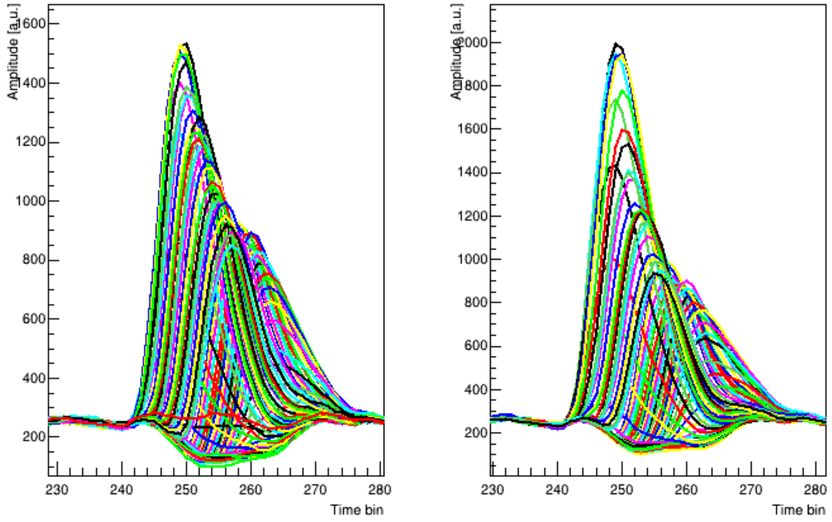
Analysis

- Dedicated analysis to reconstruct the alpha's track
- Fiducial cut: r < 2 cm
- 14 events after 13.9 days of data taking

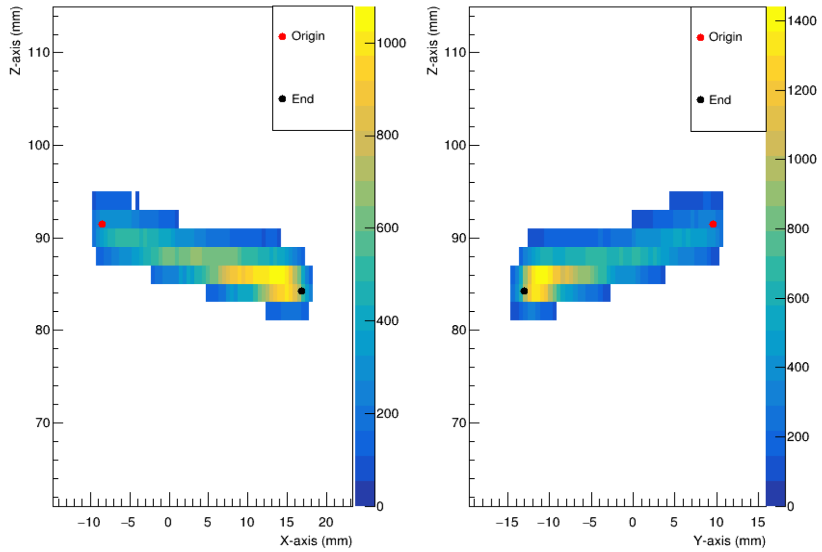


Background level (9 ± 2) x 10^{-7} alphas/cm^2·s

Signals from an alpha event



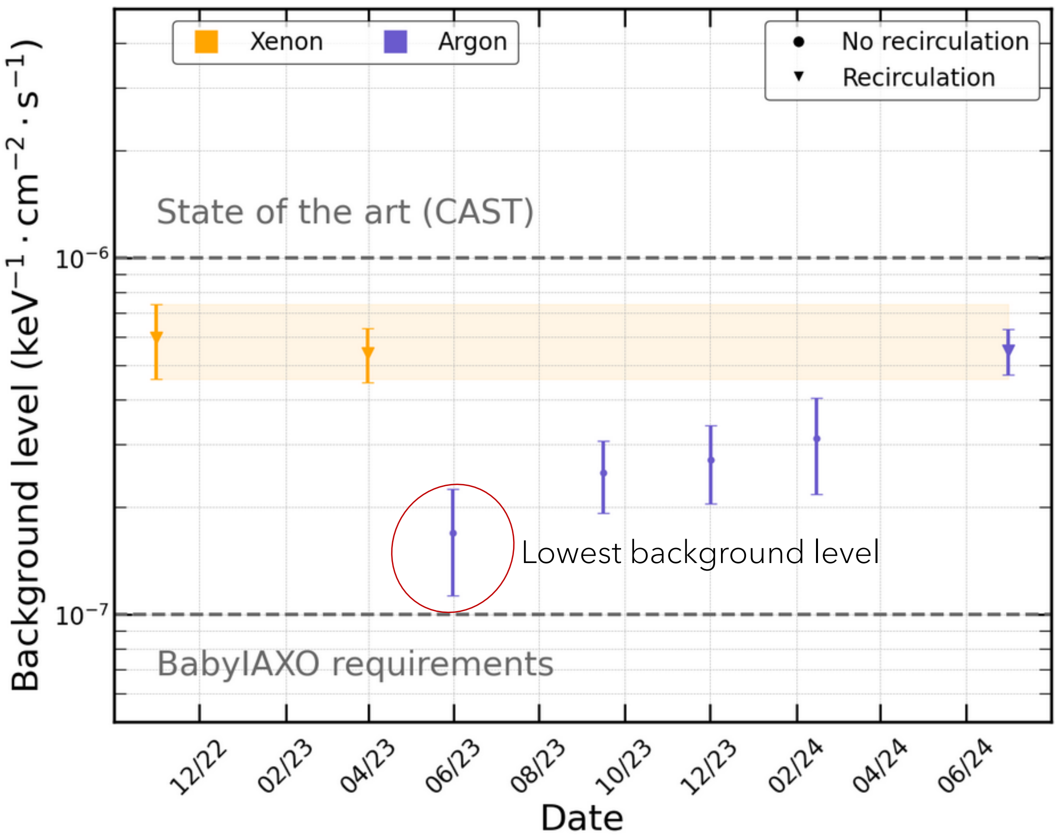
Reconstructed alpha track after analysis



JINST 17.08 (2022): P08035.

Argon background level [1-2] x 10^{-7} counts/keV·cm^2·s
- Lowest background level achieved with this technology underground

Xenon background level [5-6] x 10^{-7} counts/keV·cm^2·s
- Not compatible with previous measurements in Ar+Iso at the LSC



Low gain runs: alpha's background		
Gas	Circulation mode	Background (10^{-7} alphas / cm^2·s)
Xe-Ne-2.3%Iso	Recirculation	366 ± 15
Ar (99%-1%)	Open loop	9 ± 2
Ar (99%-1%)	Recirculation	711 ± 21

IAXO-D1 at the LSC: background status

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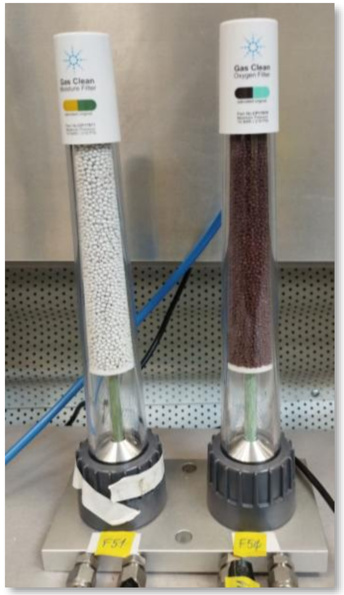
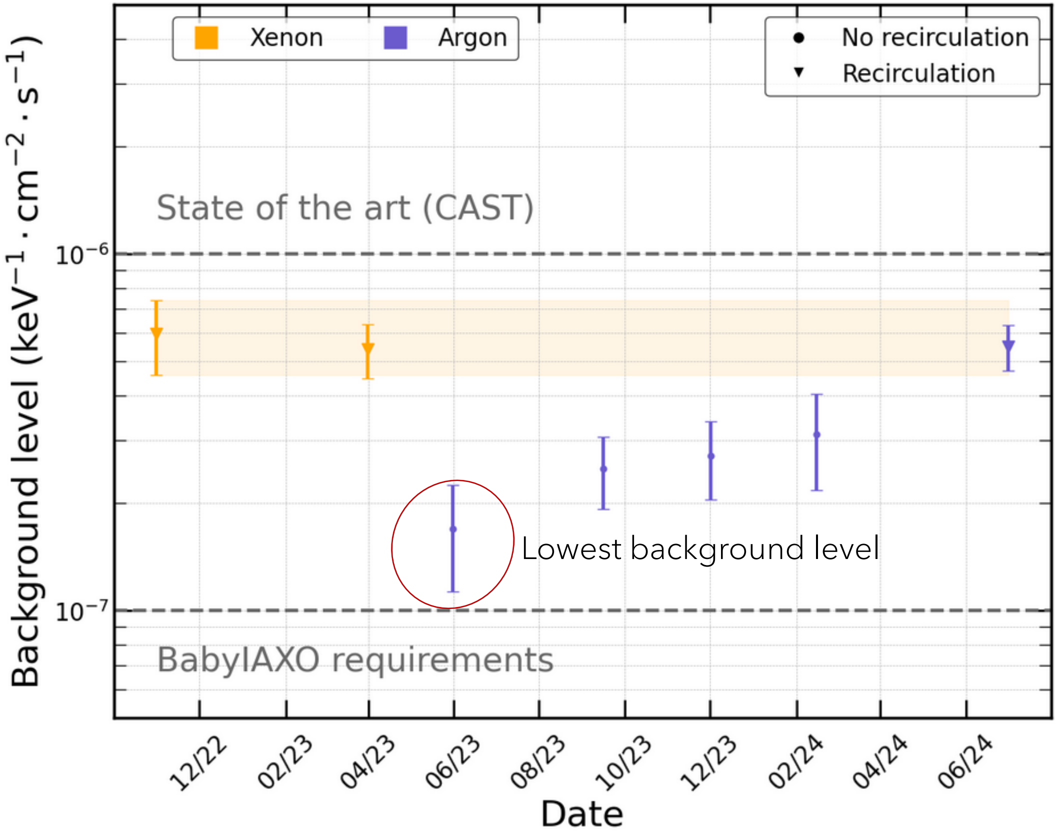
^{222}Rn contamination from filters [IEEE NSS/MIC (pp. 1-3)]





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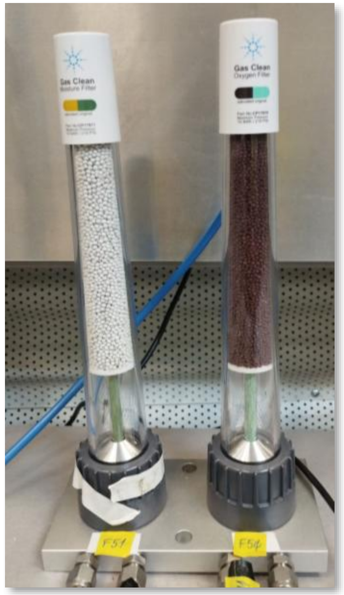
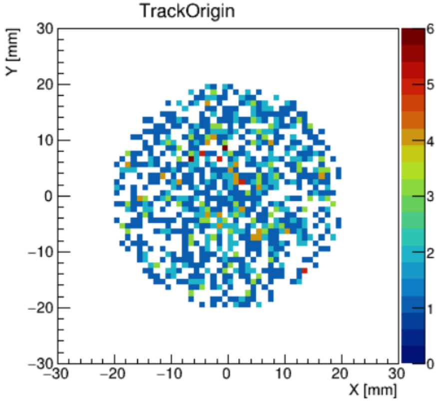
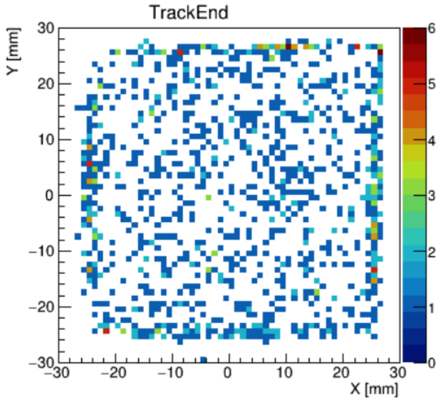
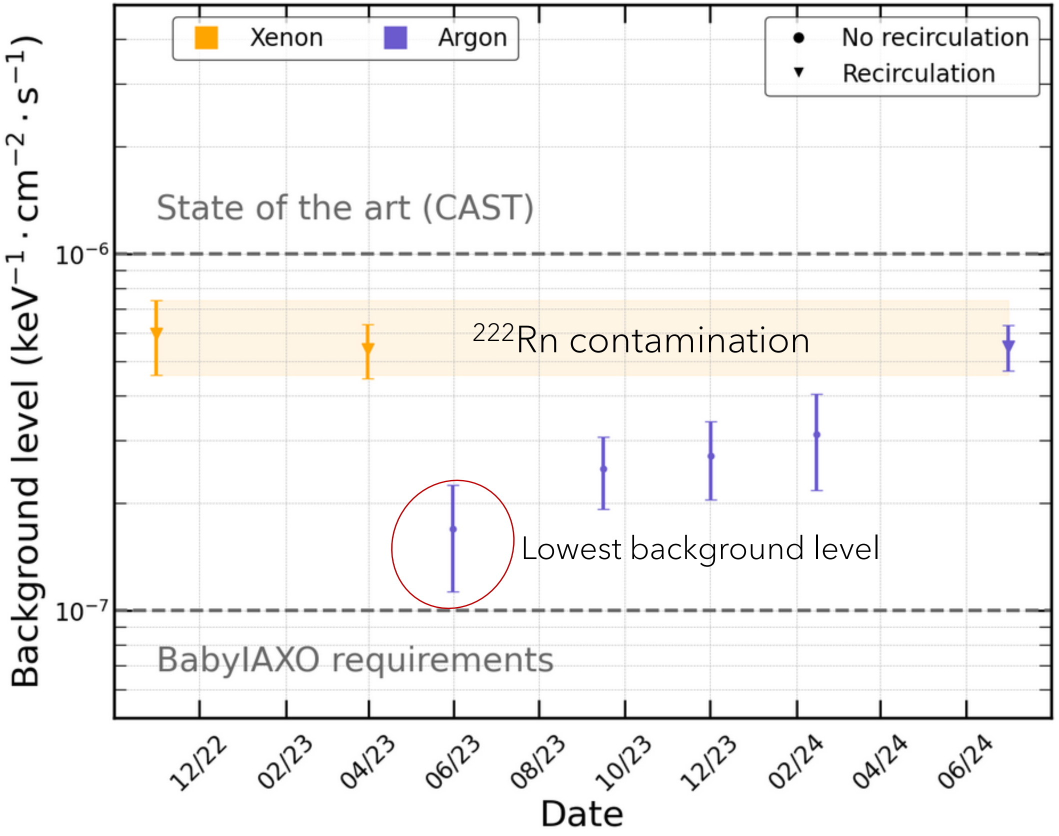








Low gain runs: alpha's background		
Gas	Circulation mode	Background (10^{-7} alphas / cm²·s)
Xe-Ne-2.3%Iso	Recirculation	366 ± 15
Ar (99%-1%)	Open loop	9 ± 2
Ar (99%-1%)	Recirculation	711 ± 21

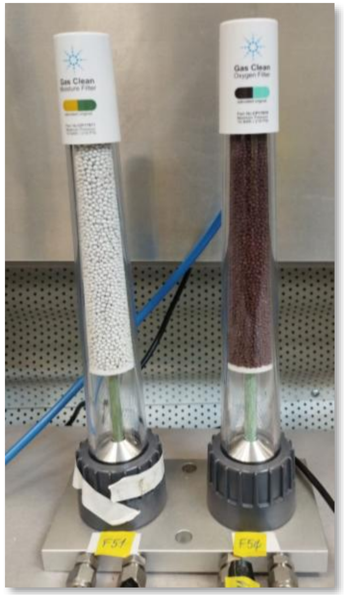
Argon background level [1-2] x 10^{-7} counts/keV·cm²·s

- Lowest background level achieved with this technology underground

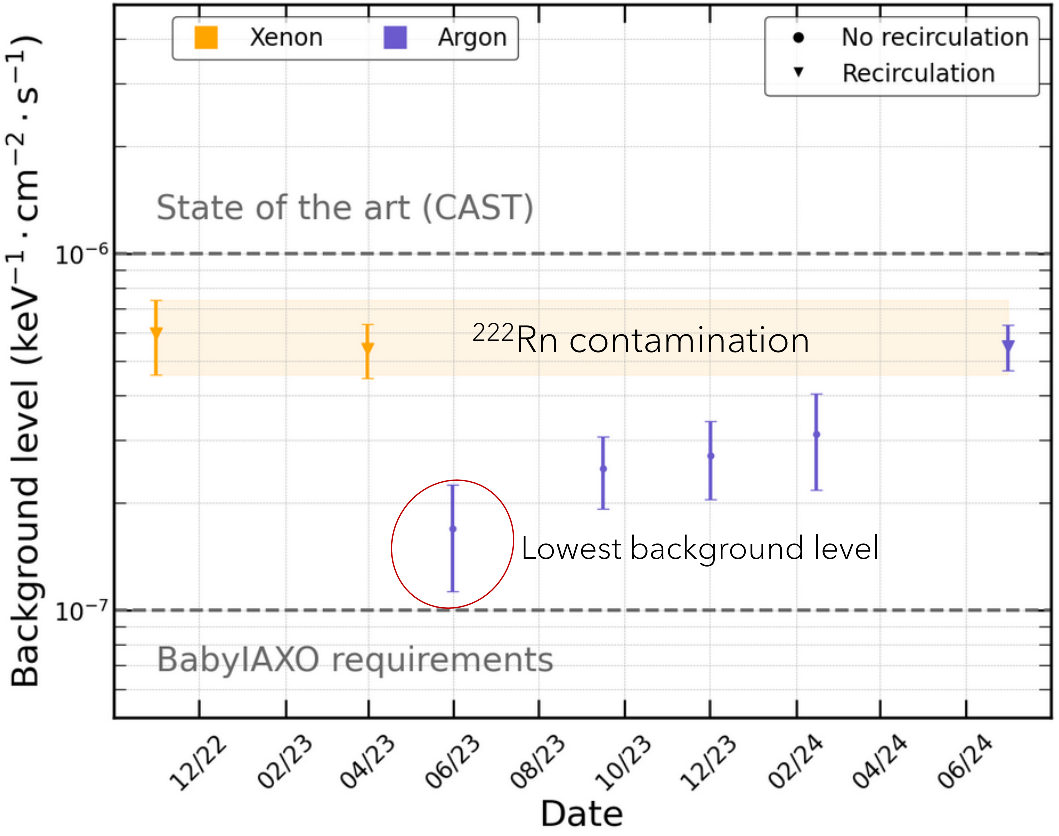
Xenon background level [5-6] x 10^{-7} counts/keV·cm²·s

- Not compatible with previous measurements in Ar+Iso at the LSC

^{222}Rn contamination from filters *IEEE NSS/MIC (pp. 1-3)*



1. Low gain runs in recirculation confirmed Rn contamination
2. Ar recirculating: compatible background level in [2,7] keV



Low gain runs: alpha's background		
Gas	Circulation mode	Background (10^{-7} alphas / cm²·s)
Xe-Ne-2.3%Iso	Recirculation	366 ± 15
Ar (99%-1%)	Open loop	9 ± 2
Ar (99%-1%)	Recirculation	711 ± 21

Summary and future prospects

- Micromegas is the baseline technology for BabyIAXO
- On-going R&D with different prototypes to explore the necessary techniques to reach the ultra-low background goals for BabyIAXO

Surface level

- Zaragoza:
  - ✓ Prototype with full veto system is under commissioning
  - ❑ Optimization of event discrimination strategies with multi-layer veto system

Underground: LSC

- ✓ Measure intrinsic background in Ar
- ✓ Underground background with Xe limited by Rn contamination from filtering system
- ❑ Different strategies to mitigate Rn contamination while operating with Xe are currently under investigation
- ❑ New radiopure electronics

Thank you for your attention

Acknowledgements

The work presented in this talk is part of the work carried out in the IAXO collaboration and funded by many agencies.

In particular, we acknowledge support from:

- The European Union's Horizon 2020 research and innovation programme under the European Research Council (ERC) grant aggreement ERC-2017-AdG788781 (IAXO+)
- The Spanish Agencia Estatal de Investigación AEI under grant PID2019-108122GB-C31 funded by MCIN/AEI/10.13039/501100011033
- The European Union NextGenerationEU/PRTR (Planes complementarios, Programa de Astrofísica y Física de Altas Energías), co-funded by Gobierno de Aragón

Additionally, M.J.P work is supported by Gobierno de Aragón with a PhD fellowship as specified in ORDEN CUS/621/2023

Backup slides

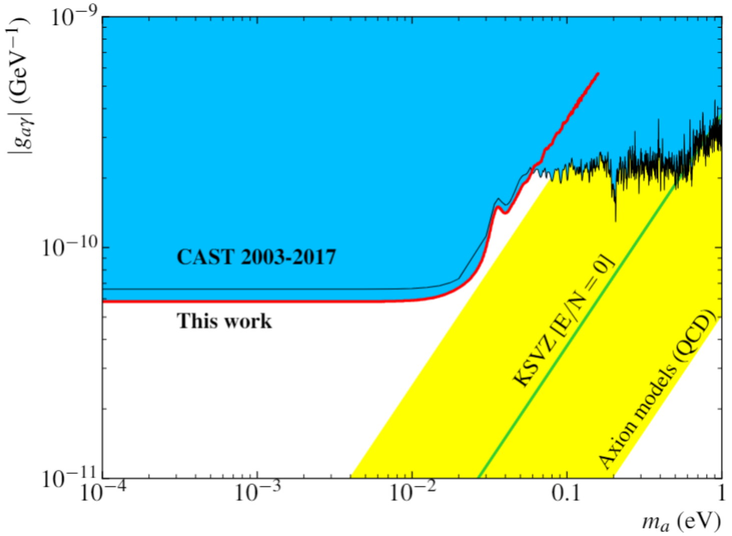
CERN Axion Solar Telescope

- More than 20 years of experience
- LHC dipole magnet
  - L = 10 m
  - Magnetic field = 9 T
- Solar tracking during sunrise and sunset
- The most sensitive helioscope so far

↓

Coupling limit $m_a < 0.01$ eV

$$|g_{a\gamma}| < 0.58 \cdot 10^{-10}\ GeV^{-1}\ (95\%\ C.L)$$



Altenmüller, K., et al. "New upper limit on the axion-photon coupling with an extended cast run with a xe-based micromegas detector." *Physical Review Letters* 133.22 (2024): 221005.

Prototype

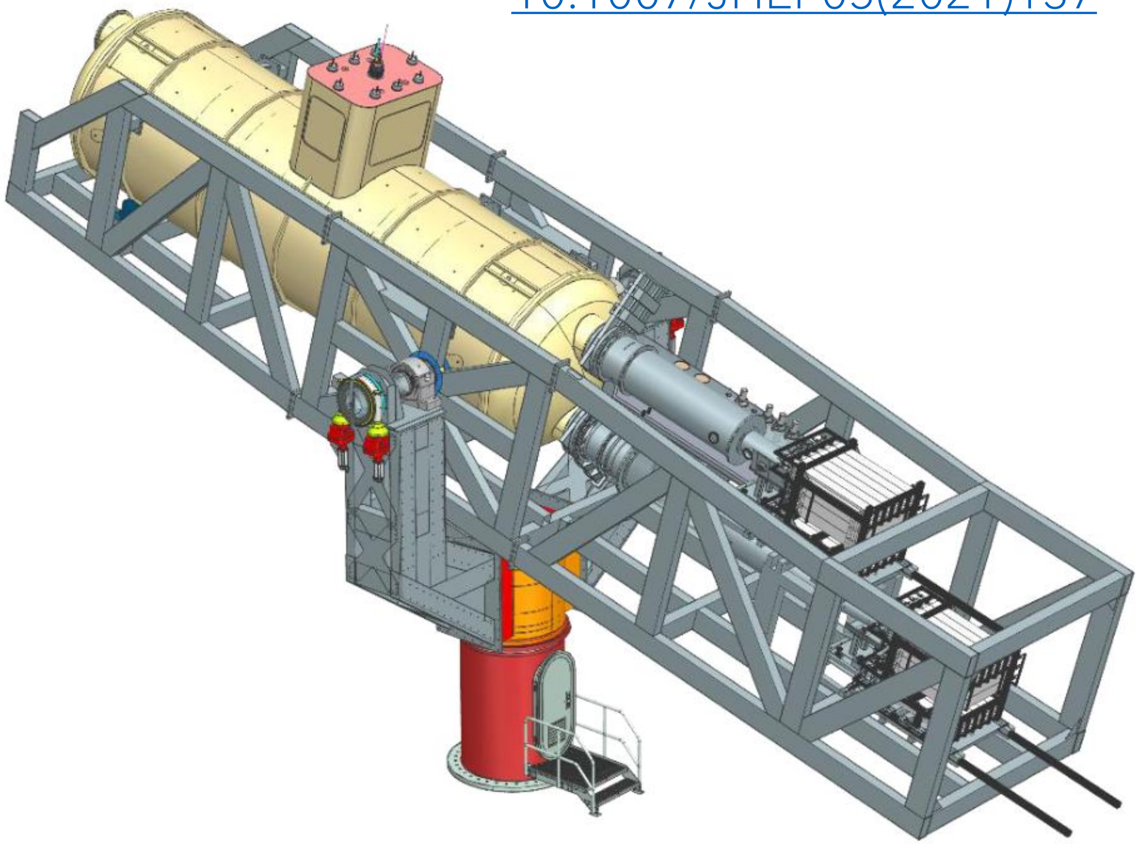
- Intermediate experimental stage before IAXO
- Two bores of dimensions similar to final IAXO bores (70 cm diameter)
  - L = 10 m, B = 3-4 T
- Detection lines representative of final ones
  - Micromegas baseline
- Magnet will test design options of final IAXO magnet
- Test and improve all systems. Risk mitigation for full IAXO

Physics

- Will also produce relevant physics outcome

FOM 100 x CAST

10.1007/JHEP05(2021)137



International Axion Observatory

FOM 10.000 x CAST

Toroidal magnet: 8 bores of 60 cm diameter

- L = 20 m, B = 5.4 T

Dedicated x-ray optics

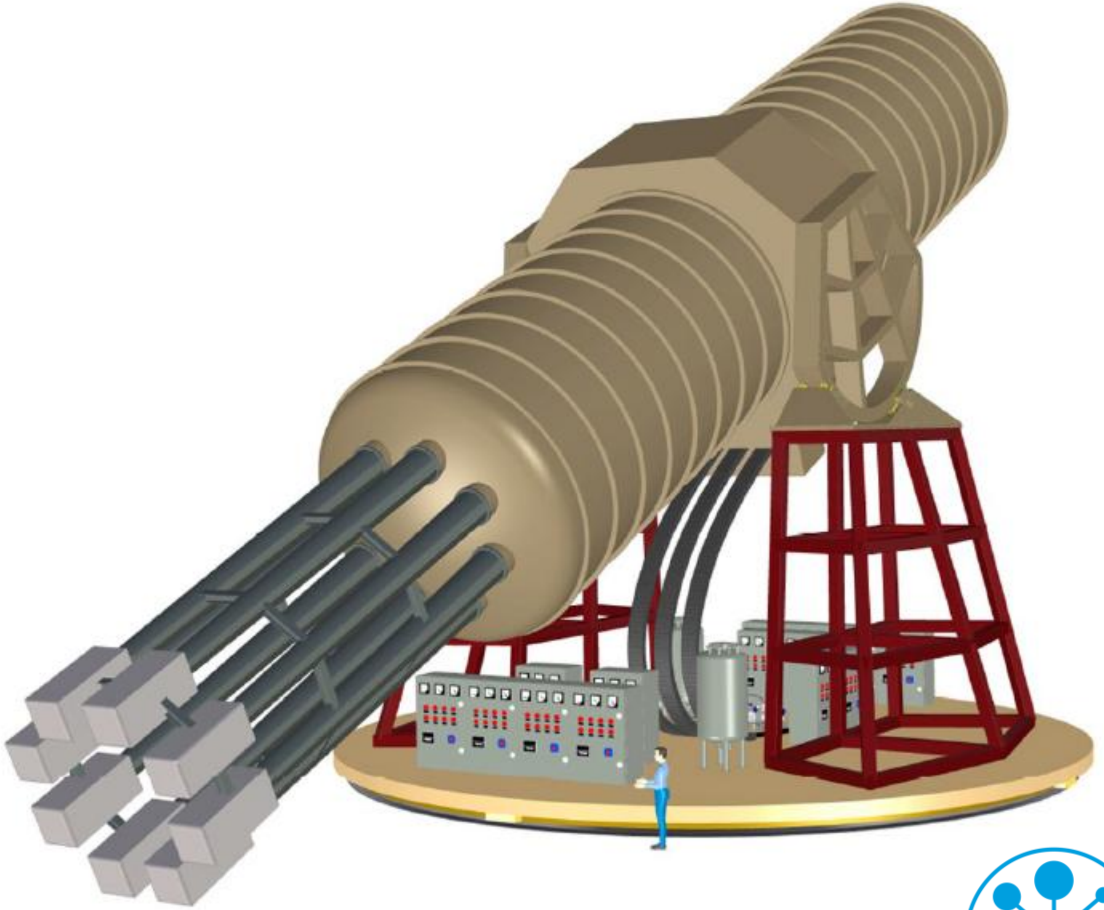
- 0.2 cm^2 focal spot

Tracking system

- Based on CTA
- 50% Sun-tracking time

8 detection lines

- Micromegas, GridPix, Metalic Magnetic Calorimeter, Transition Edge Sensors, Silicon Drift Detectors



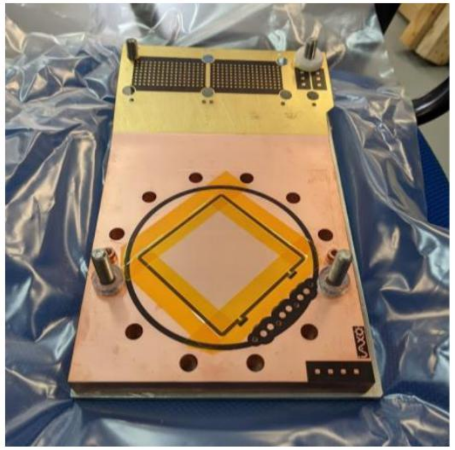
10.1088/1748-0221/9/05/T05002

X-RAY DETECTOR REQUIREMENTS

- High x-ray detection efficiency in the ROI (0-10 keV)
- Ultra low background levels:
  - 10^{-7} c/keV/cm²/s (BabyIAXO)
  - 10^{-8} c/keV/cm²/s (IAXO)

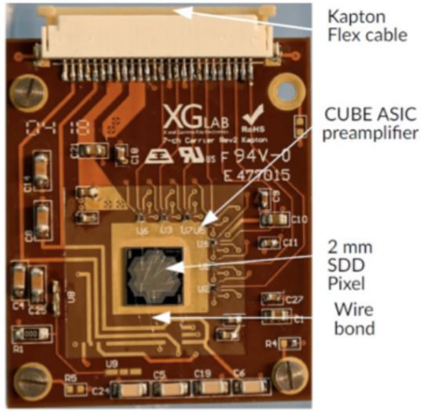
IDEALLY

- Low energy threshold (100 eV)
- Good energy resolution

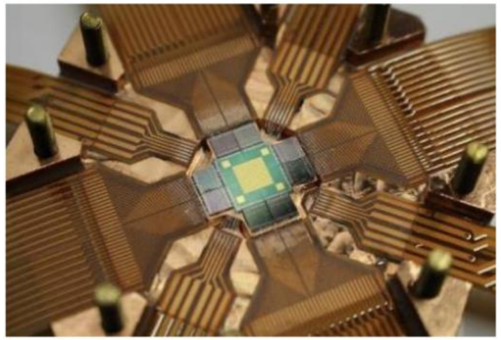


Microbulk Micromegas TPC
(U. Zaragoza and CEA-Saclay)

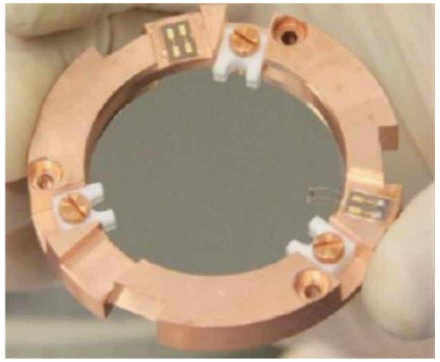
GridPix TPC
(U. Bonn)



SDD: Silicon Drift Detectors
(Technical U. Munich)



MMC: Metallic Magnetic Calorimeters
(U. Heildeberg and CEA-Saclay)

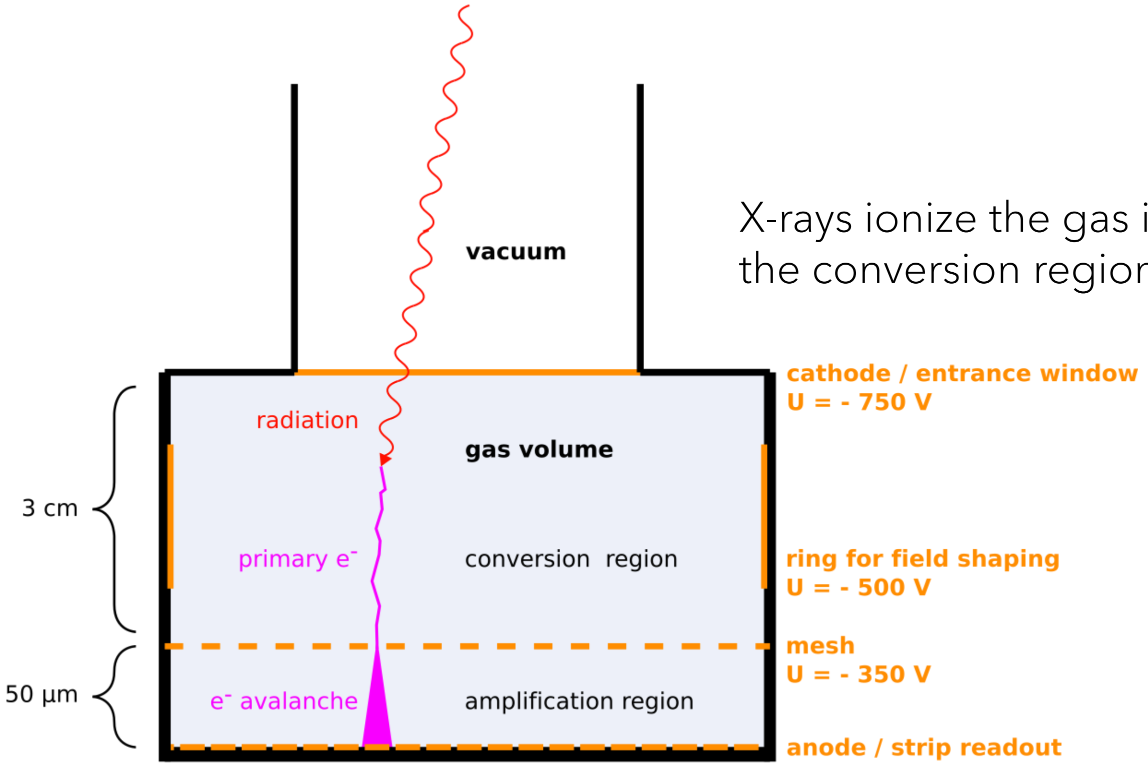


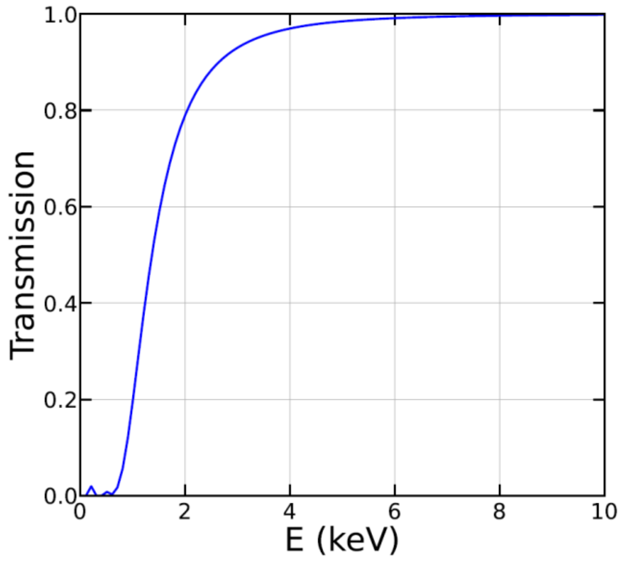
TES: Transition Edge Sensors
(U. Zaragoza-INMA ICMAB-CSIC IJCLab)

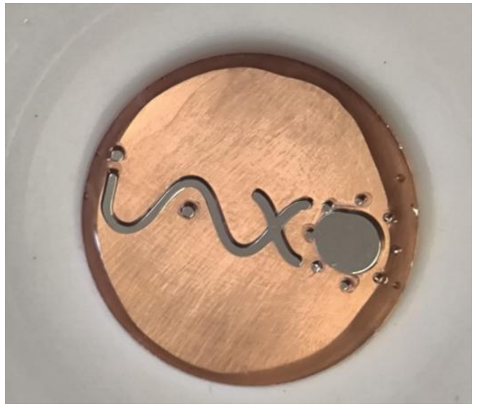
Micromegas x-ray detectors

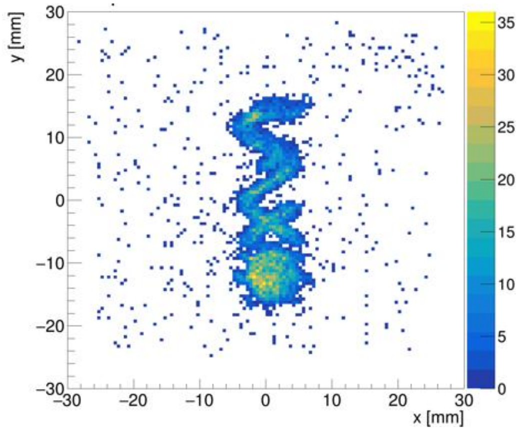
X-ray reaches the active volume through an aluminized mylar window (4 µm)

X-rays ionize the gas in the conversion region





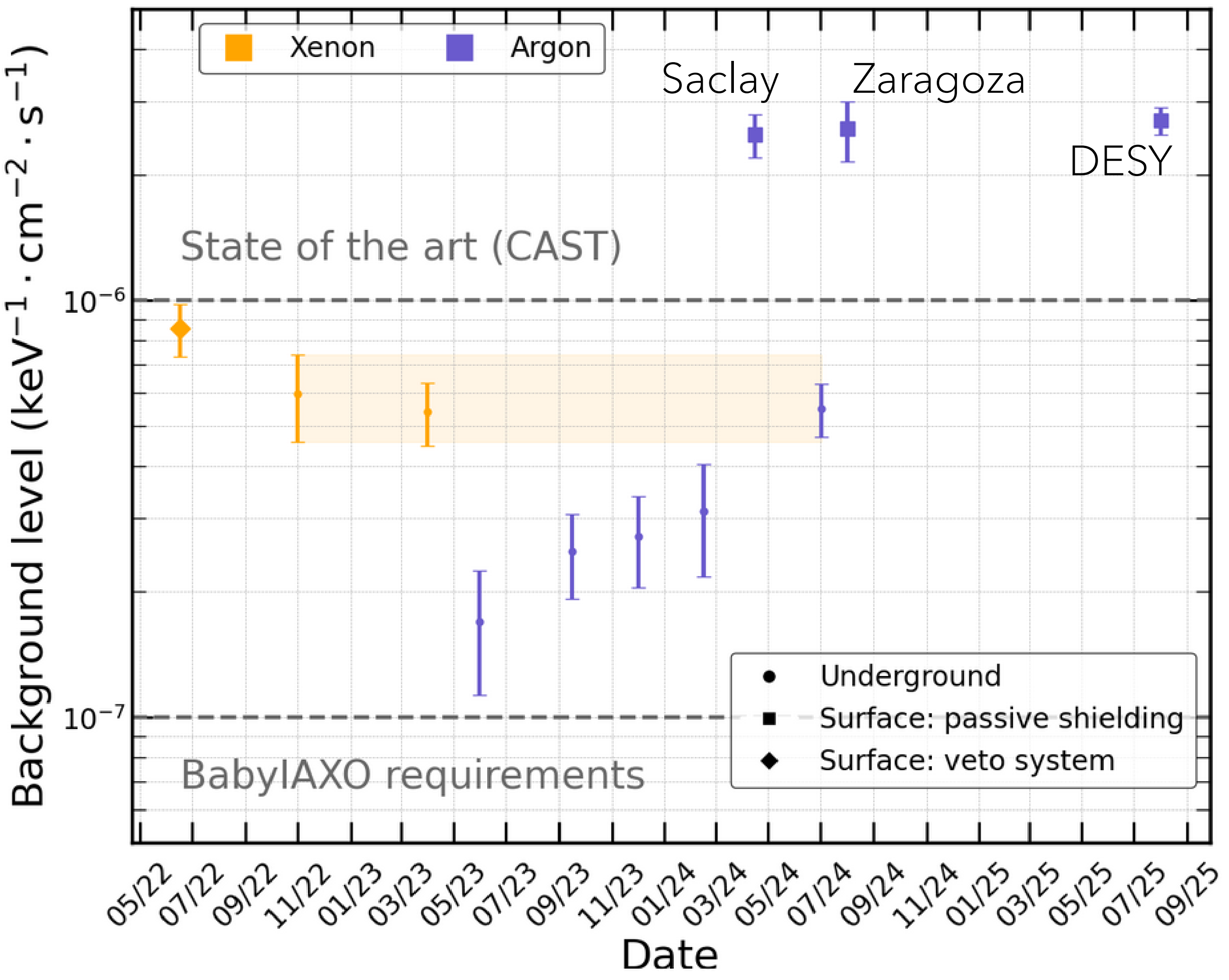




The electrons pass through the mesh holes and are amplified

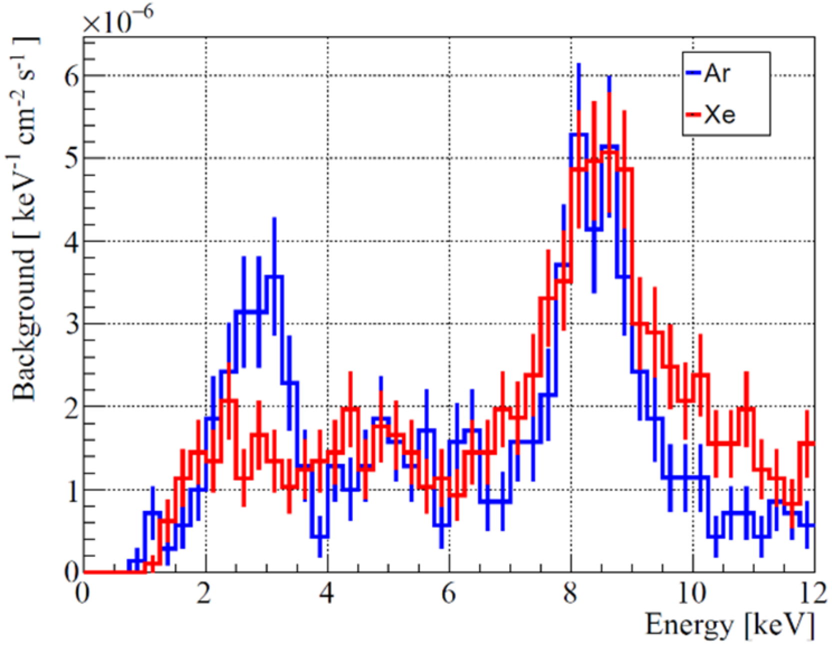
Electron-ion movement induced signals in the mesh and strips

BabyIAXO Micromegas background status

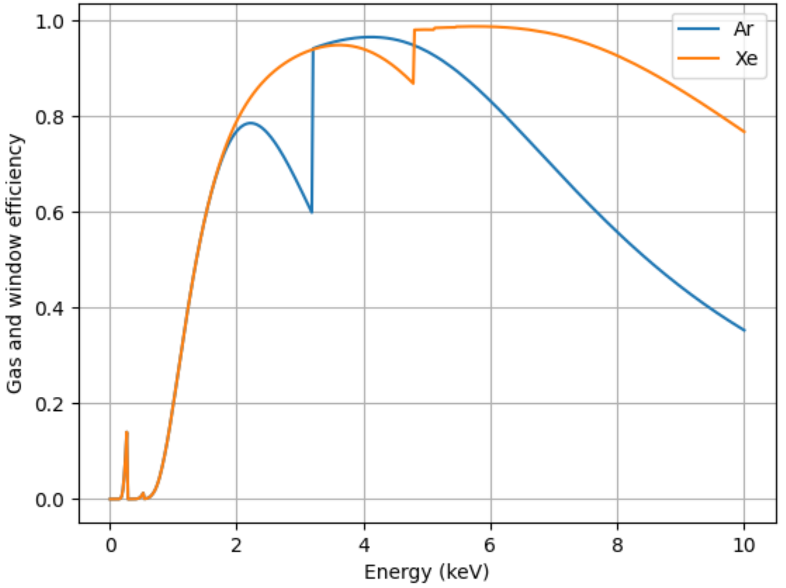


Gas election: Xe-based vs Ar-based mixtures

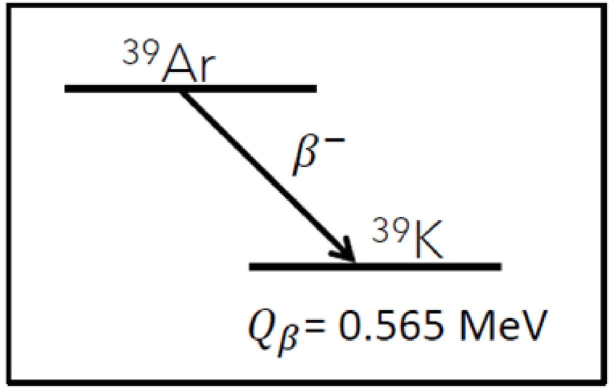
- BabyIAXO background goal is < 10^{-7} c·keV^{-1}·cm^{-2}·s^{-1}
- Goals of the IAXO-D1 MM underground setup:
  - Test of performance of different gas mixtures (Ar-based and Xe-based)
  - Study the intrinsic detector background (internal and inner shielding) with the different gases



Typical background spectra with Ar-based mixtures has the escape peak at ~3 keV (solar axion spectra has a peak expected in 3 keV)



Xe has a better x-ray efficiency in the ROI



Intrinsic background in AAr is limited by ^{39}Ar, $T_{1/2}$ = 269 years

Gas election: Isobutane

Ar + Isobutane gas mixtures with microbulk micromegas

More isobutane: higher voltages →

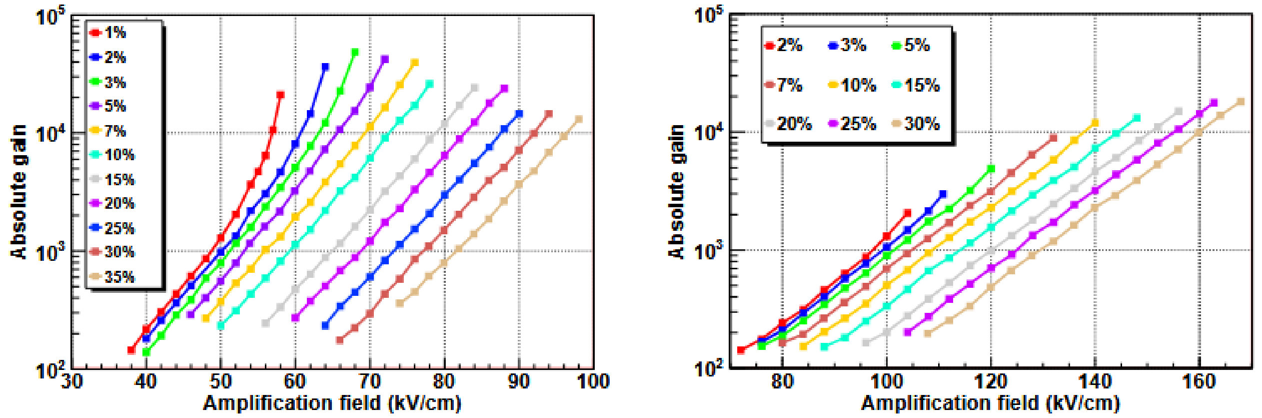


Figure 6. Dependence of the absolute gain with the amplification field for two microbulk detectors with gaps of 50 (left) and 25 μm (right) in argon-isobutane mixtures. The maximum gain of each curve was obtained just before the spark limit. The percentage of each series corresponds to the isobutane concentration.

Better energy resolution with higher % of isobutane →

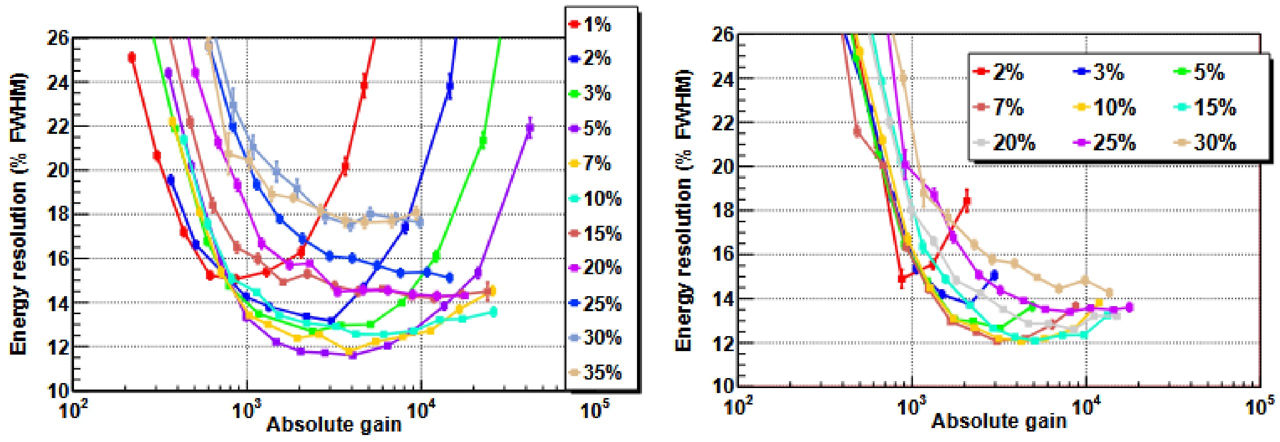
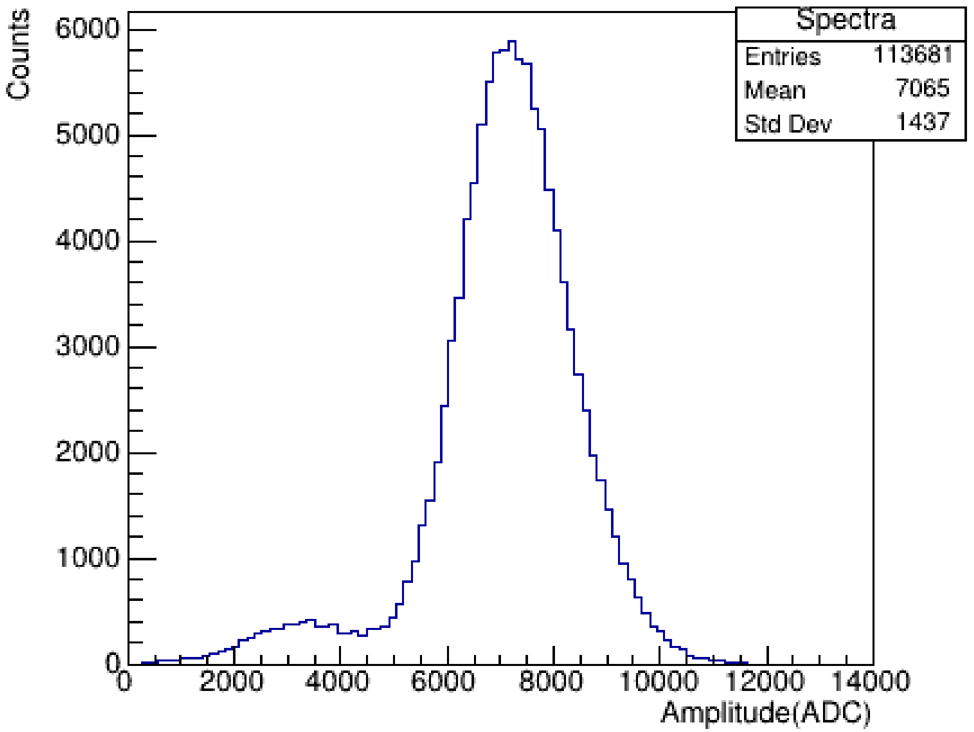


Figure 7. Dependence of the energy resolution with the absolute gain for two detectors of 50 (left) and 25 μm-thickness-gap (right) in argon-isobutane mixtures. The maximum gain of each curve was obtained just before the spark limit. The percentage of each series corresponds to the isobutane concentration.

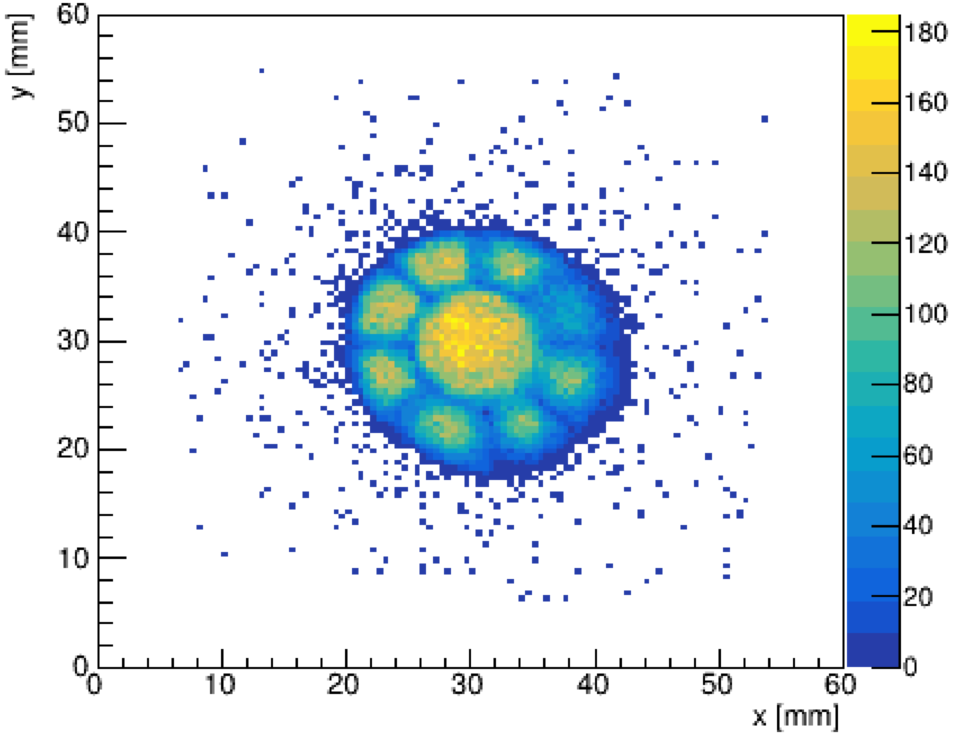
https://iopscience.iop.org/article/10.1088/1748-0221/7/04/P04007

Gas: 99% Ar + 1% Isobutane @ 1.4 bar

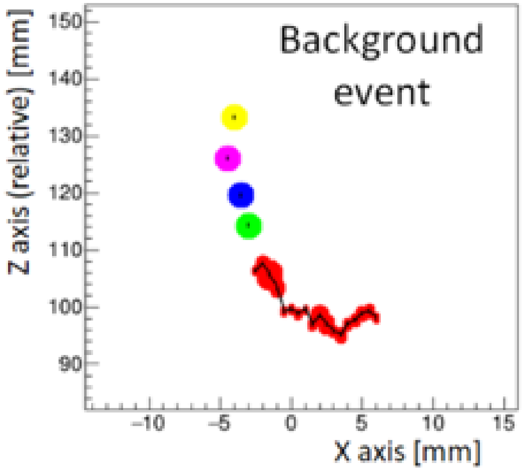
Energy spectra

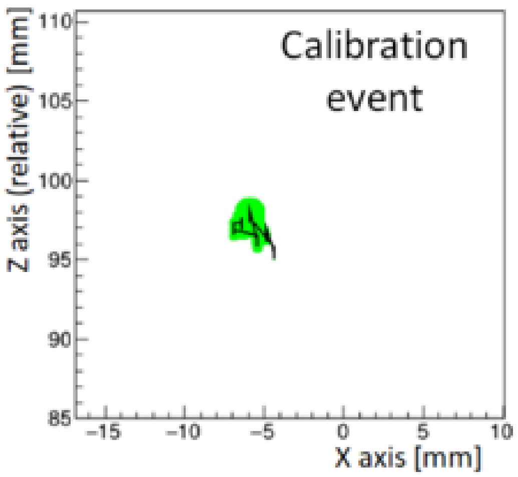


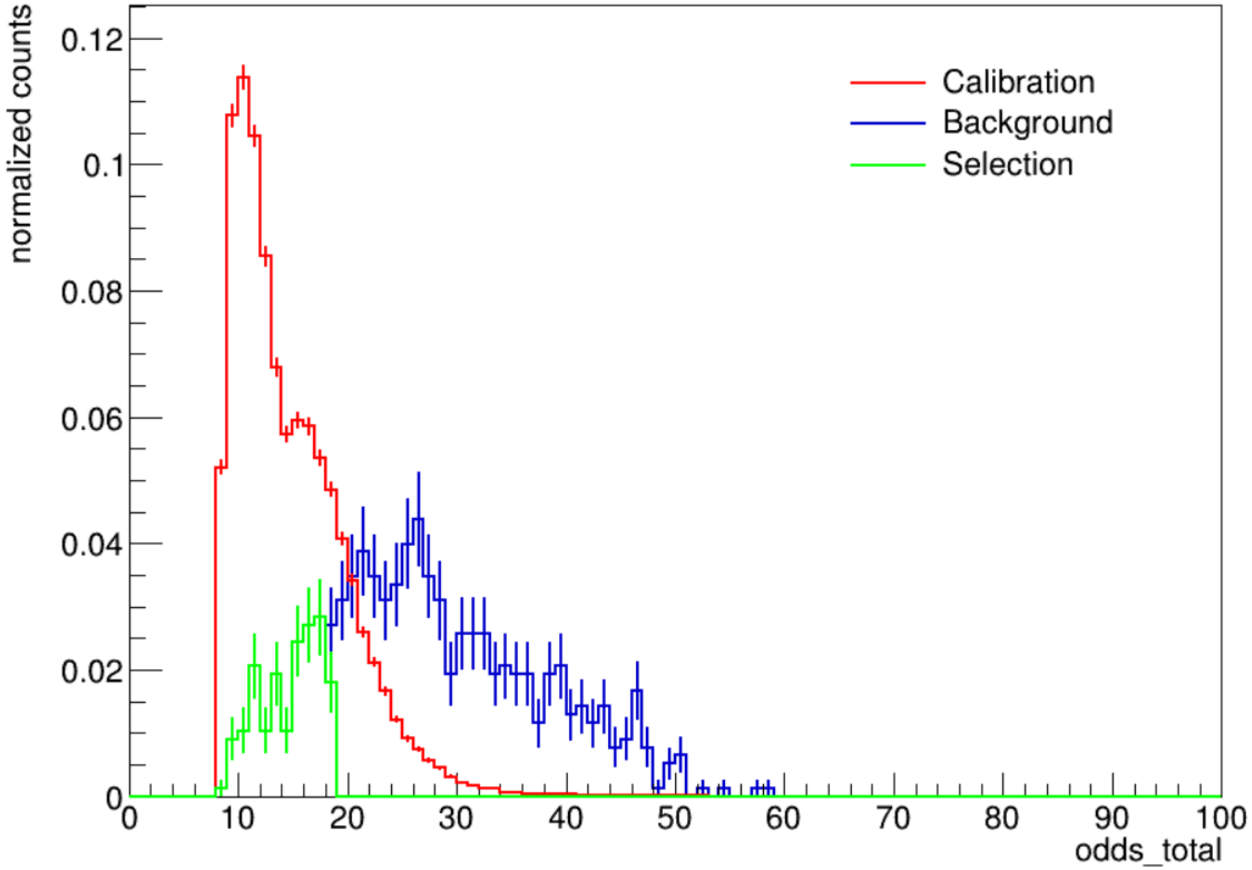
Hitmap



- Background rejection based on event topology
  - Log-odd distribution is computed for a set of given observables for calibration and background events
  - Cut efficiency fixed at 80% for calibration events in the 5.9 keV peak
- Implemented in [REST-for-Physics]



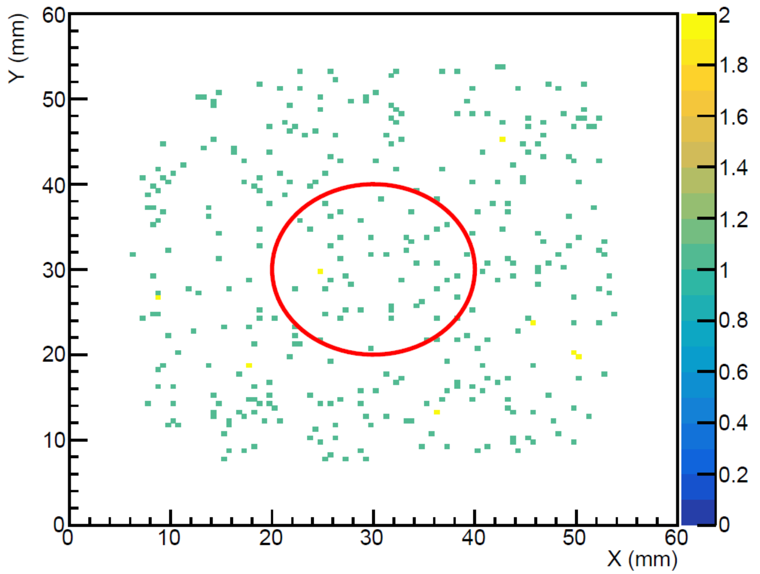


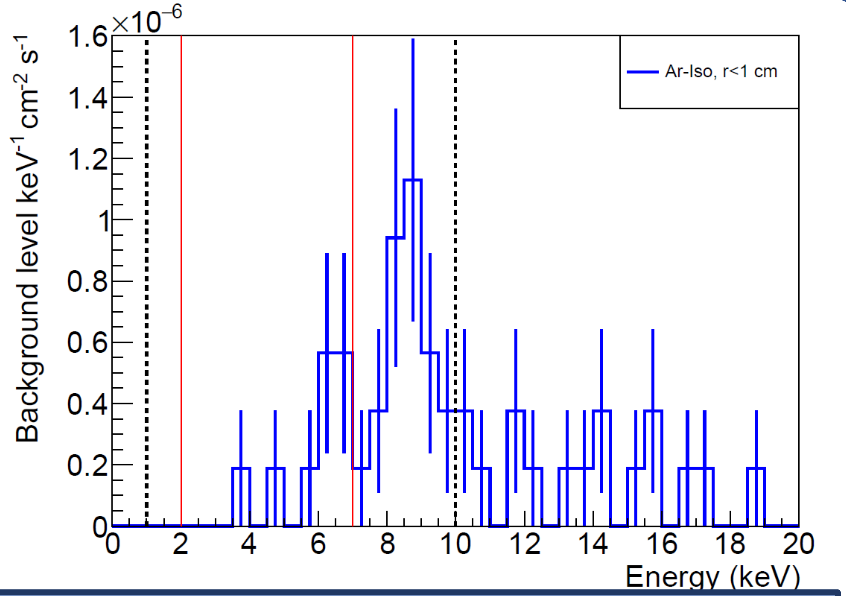


Nominal gain

Data taking conditions

- 99%Ar-1%Isobutane (premixed)
- HVMesh = 320V-325V
- HVCathode = 750V
- P = 1.25 bar
- Gas flow 2l/h



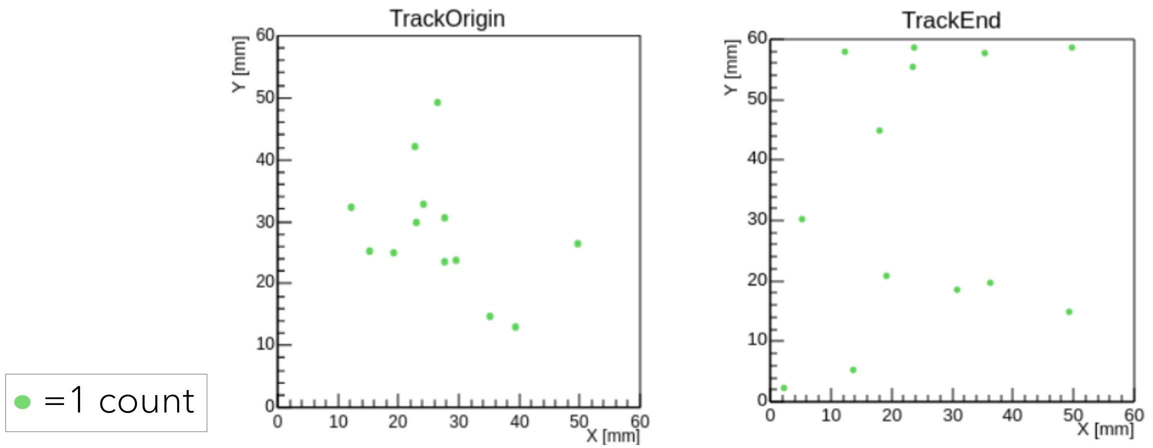


Background level after 39.15 days of data taking: 9 counts in [2-7] keV
$(1.7 \pm 0.6) \times 10^{-7}$ counts/keV·cm^2·s

HVMesh = **250 V**

✓ Compatible rate at the beginning and end of the gas bottle

14 events inside r<2 cm after 13.9 days
$(9 \pm 2) \times 10^{-7}$ alphas/cm^2·s



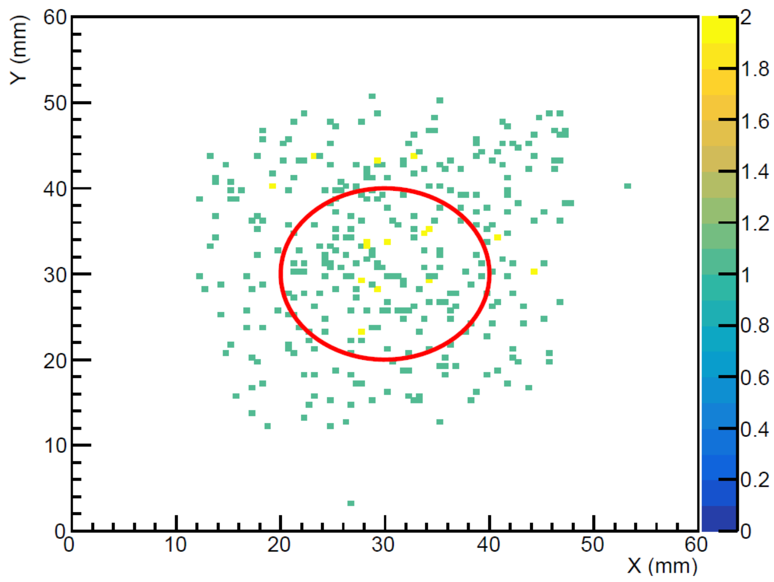
Background measurements: Xenon in recirculation

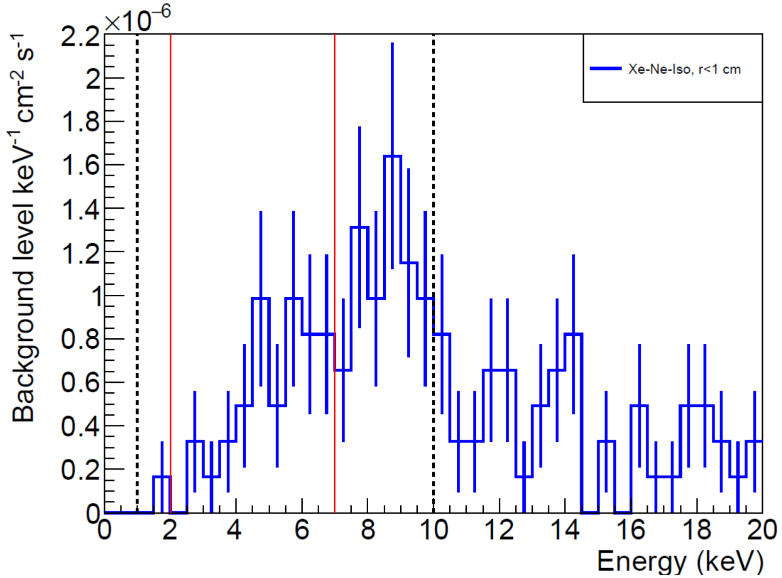
Nominal gain

Data taking conditions

- Xe-Ne-Isobutane (premixed)
- HVMesh = 395V
- HVCathode = 750V
- P = 1.0 bar
- Gas flow 2l/h (recirculating)

→ Background rejection based on event topology





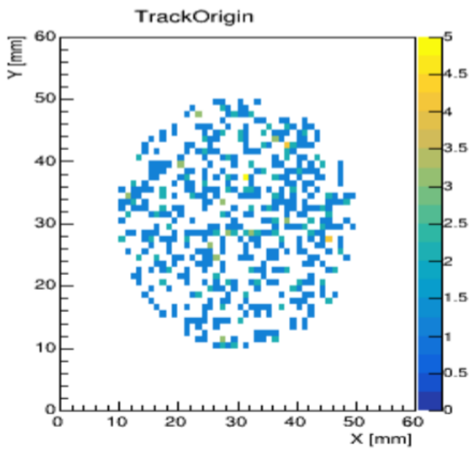
Background level after 45 days of data taking: 33 counts in [2-7] keV , $(5.4 \pm 0.9) \times 10^{-7}$ counts/keV·cm²·s

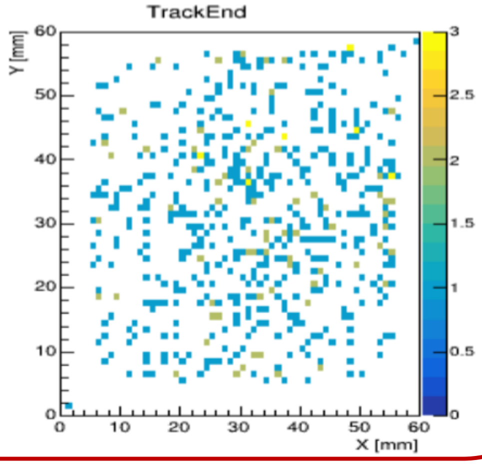
Low gain

Same data taking conditions, except HVMesh = 395V →**250 V**

→ Dedicated analysis to reconstruct the alpha tracks

608 events inside r<2 cm after 15.3 days $(3.66 \pm 0.15) \times 10^{-5}$ alphas/cm²·s

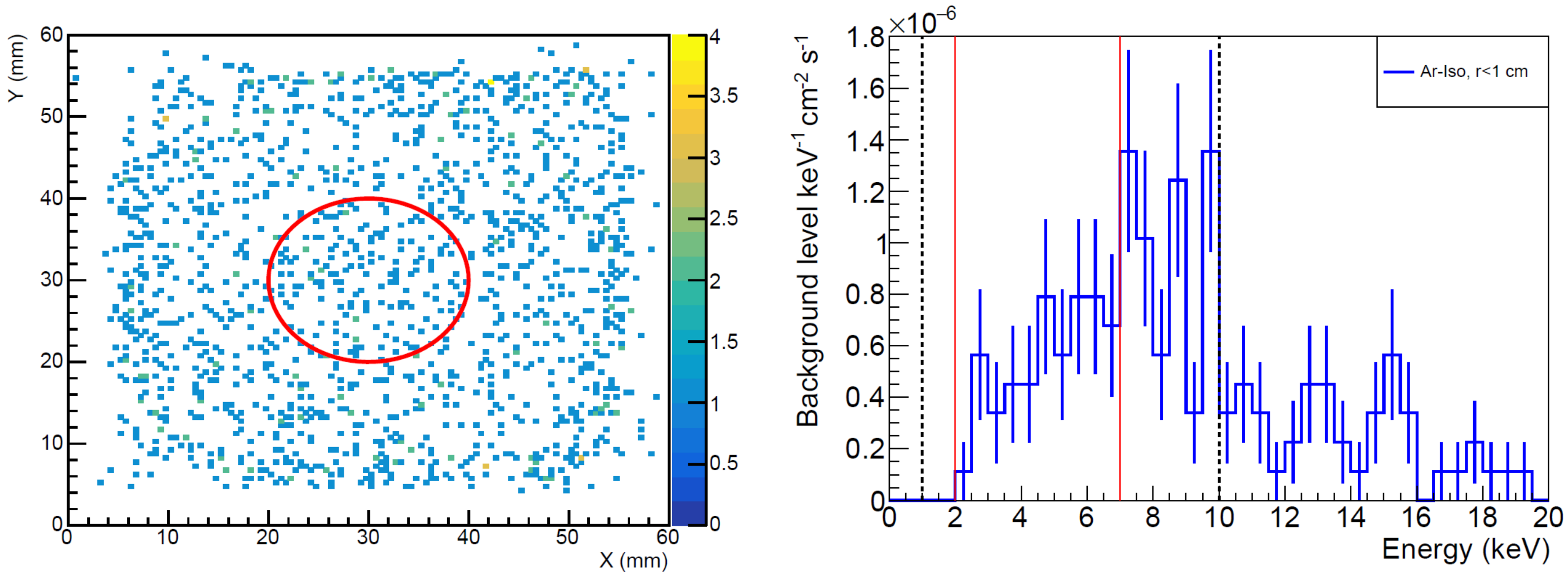




Background measurements: Argon in recirculation

Nominal gain

Data taking conditions
- 99%Ar-1%Isobutane (premixed)
- HVMesh = 320V
- HVCathode = 750V
- P = 1.25 – 1.4 bar
- Gas flow 2l/h

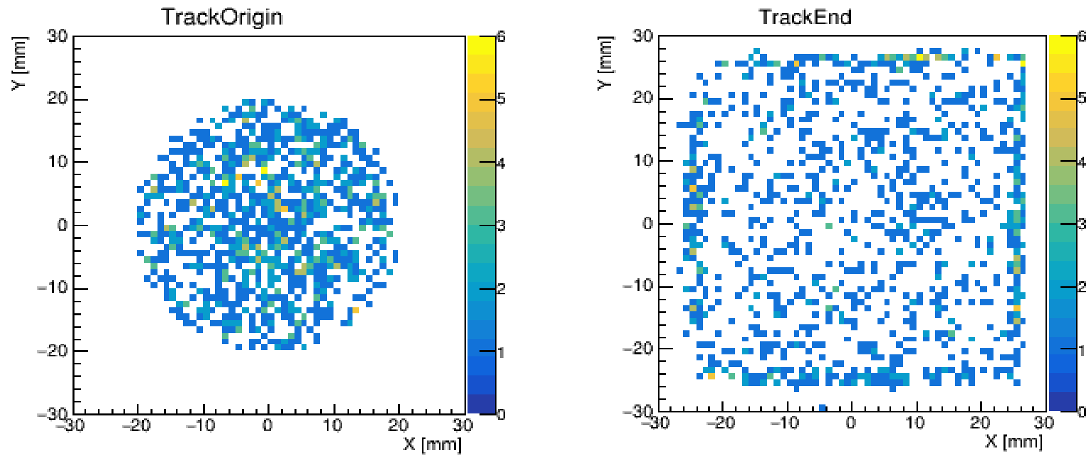


Background level after 65 days of data taking: 49 counts in [2-7] keV , (5.5 ± 0.8) x 10^{-7} counts/keV·cm^2·s

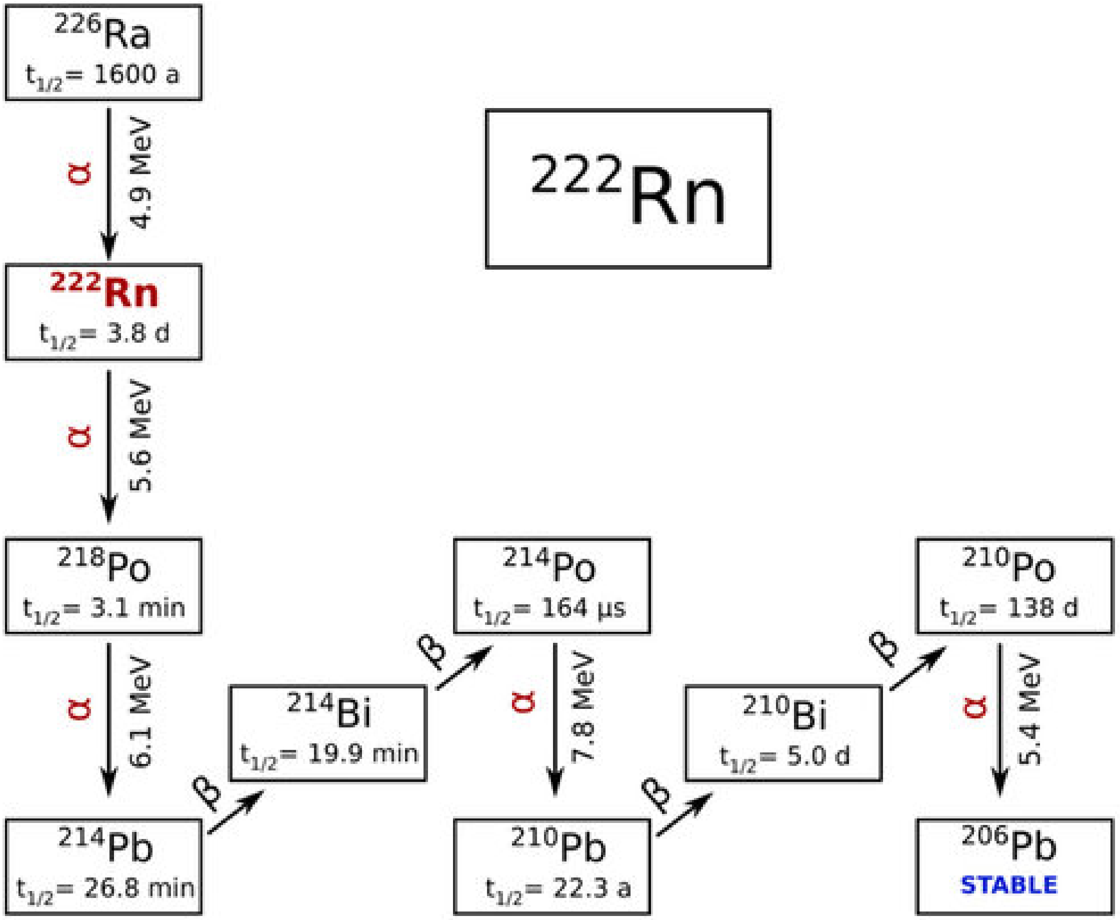
Low gain

HVMesh = **250 V**

1159 events inside r<2 cm after 15 days (7.11 ± 0.21) x 10^{-5} alphas/cm^2·s



Radon



β emitters in the Rn decay chain but also, γ and x-rays associated

Energy (keV)	Intensity (%)*	Type	Origin*	Levels Start*	Levels End*	Parent
12.56455 (-)	22.0 (5)	X_L	Bi			Pb-210
12.89 (-)	12.42 (22)	X_L	Bi			Pb-214
72.805 (-)	7 (4)	$X_{K\alpha 2}$	Pb			Tl-210
72.8725 (-)	3.9 (8)	$X_{K\alpha 1}$	Tl			Hg-206
74.8157 (-)	6.26 (12)	$X_{K\alpha 2}$	Bi			Pb-214
74.97 (-)	11 (6)	$X_{K\alpha 1}$	Pb			Tl-210
77.1088 (-)	10.47 (20)	$X_{K\alpha 1}$	Bi			Pb-214
84.9527 (-)	3.8 (19)	$X_{K'\beta 1}$	Pb			Tl-210
87.347 (-)	3.59 (9)	$X_{K'\beta 1}$	Bi			Pb-214